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THE PROCESSES OF VISUAL PERCEPTION AND THE IMPLICATIONS
FOR OPTIMISATION OF DISPLAYS(U) ROYAL SIGNALS AND RADAR
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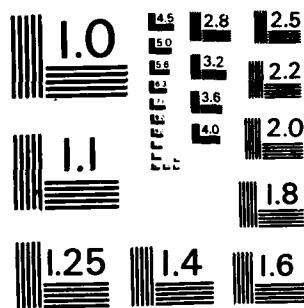
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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Report No 83001

Title: THE PROCESSES OF VISUAL PERCEPTION AND THE IMPLICATIONS
FOR OPTIMISATION OF DISPLAYS

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SUMMARY

This report has been written after several seminars within RSRE had highlighted a number of disturbing facts. Firstly, there is very little dialogue between the designers of displays and the vision researchers. Secondly, although a great deal of information exists on the performance of the eye, it is often obscure and the practical implications are not clear. Thirdly, for a display engineer who is not necessarily interested in the fine detail of the visual mechanisms, sources of practical data covering the whole subject of human vision are scarce.

A brief description of the physical properties of the eye is given together with an account of the various methods of measuring observer performance. The diagrams are provided as a means of indicating general trends with a minimum of descriptive narrative. A broad bibliography is included so that those interested in specific topics can follow them up.

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RSRE REPORT NO 83001

THE PROCESSES OF VISUAL PERCEPTION AND THE IMPLICATIONS
FOR OPTIMISATION OF DISPLAYS

R Home

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1 INTRODUCTION

This review is concerned with the transfer of information from a display to the visual cortex. The visual tasks associated with displays can be broadly divided into four categories:

- i Simple detection (eg indicator lamp on or off; movement of a needle).
- ii Reading α-numerics.
- iii Surveillance of picture imagery.
- iv Tracking and aiming.

The transfer of information must be optimised, in each case, if maximum use is to be made of the available data. Firstly, a brief description of the visual system will be given, leading to a consideration of each of the tasks listed. The amount of relevant information on this subject is vast so a precis will be given of the various topics together with a list of references for those who wish to follow up a particular interest.

2 THE VISUAL SYSTEM

Although in its physical construction the eye possesses marked similarities to a camera, a deeper study reveals that this is a poor analogy. The eye has evolved to cope with its natural environment, and for this reason may experience difficulty in adapting to a display which departs from that description. The display engineer's problem is to produce a display which allows the visual system to adapt optimally, producing efficient information transfer for the task at hand. In most cases, the resultant display is a compromise between what the visual system would require ideally, and that which can be provided practically and economically.

The eye is not simply an optical system which feeds an image directly into the cortex. Processing takes place continually at all levels, even the basic optical parameters being modified as a direct result of information received at the receptor (detector) array, ie there is a continual feedback in the system. In fact, the whole system is adaptive. This has the advantage of requiring less strict control of the display parameters by the designer, but has the disadvantage that it makes predictive modelling of system performance very difficult because the state of the visual system is more difficult to define than a system with fixed parameters. A physical description of the eye will give some indication of its adaptive capabilities.

2.1 General Construction

A simplified diagram of the eye is shown in Figure 1. The main optical refracting element is the cornea. Beyond this are two chambers separated by a thick, crystalline lens, the function of which is to provide focussing accommodation about the basic dioptric power of the eyeball. Immediately before the lens is an aperture stop in the form of a variable iris diaphragm. A primary image is formed on the retina which comprises a matrix of receptors, the density of which is maximal at the fovea. This is the region onto which the information at the centre of attention is focussed. At the retina, the optical image is transposed into a physiological image by chemical bleaching within the receptors. This is a cumulative

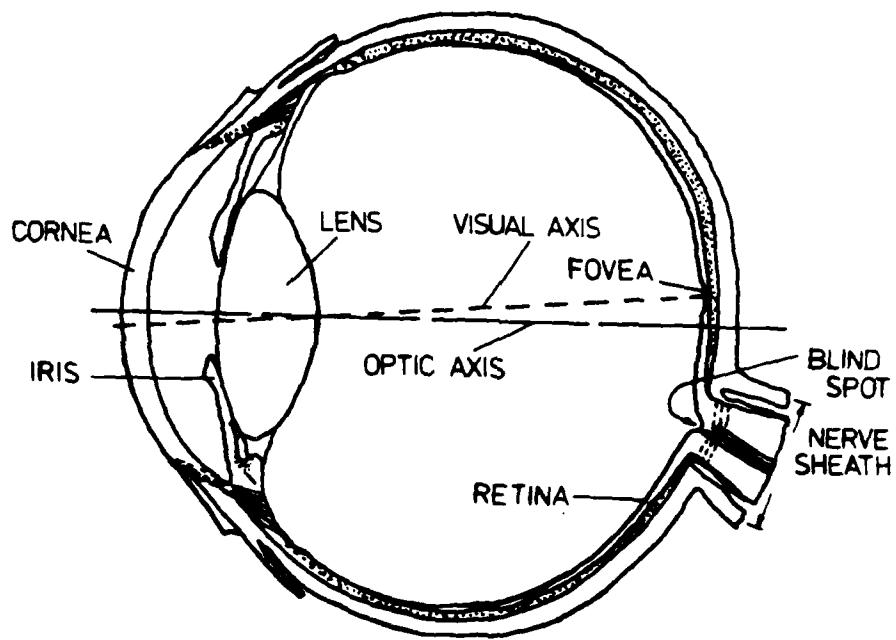


FIG.1 SCHEMATIC HUMAN EYE [SIMPLIFIED]

process, and to avoid fading of a constant image, the eye operates as an AC system. Eye movements provide a time-varying signal at the receptors. There are three distinct involuntary movements of the eye.

a Tremor

This is a permanent slight oscillation of between 20 and 200 Hz (Riggs et al 1953; Ditchburn, 1958) with a mean excursion of 0.2 arc min. Tremor is the residual oscillation resulting from muscle balance in a system designed to react very rapidly to dynamic stimuli.

b Saccades

These are fast excursions or "flicks" with a mean magnitude of 5.6 arc min, but their magnitude can be as large as 1 degree. A typical saccade takes place in 0.3 sec, successive movements occurring at intervals ranging between 0.1 and 1.0 sec (Ford et al, 1959; Ditchburn and Foley-Fisher, 1967). Saccades are thought to be corrective movements guided by retinal control (Cornsweet, 1956).

c Intersaccadic Drift

This is a relatively slow movement which is thought to result from residual muscular imbalance (cf typical DC servo system). It has a typical rate of about 1 arc min sec⁻¹ (Adler and Fliegelman, 1934).

Various eye movements can be elicited by movement, or apparent movement, of a stimulus. The resultant eye tracking mechanism (known as pursuit movement) is a combination of two types of motion; a rapid saccadic flick which is driven by a positional error function, and a slower smooth motion, driven by a velocity error function. The actual form of these pursuit eye movements depends on the time constants of the visual mechanisms and that of the stimulus. (See, for example, Robinson, 1965 and 1968.) The fact that certain stimulus movements, or apparent movements, may distract the eye from a primary task, must be borne in mind by the display designer.

In binocular vision there exists a vergence movement mechanism which is strongly linked to the accommodation (focussing) process (Fry, 1937; Fincham and Walton, 1957). Convergence is the eye movement by which the two visual axes are made to coincide at the position of focus. Although there is a fairly wide tolerance on what the visual system will accept as accommodation and vergence are forced apart, optimum visual performance is achieved only when the two mechanisms are in correspondence (Burton and Home, 1980). A deeper explanation is given later in this section.

The remainder of this section deals with specific mechanisms within the eye, all of which exhibit the ability to adapt to the visual environment.

2.2 The Pupil

The iris diaphragm is the aperture stop of the eye. This pupil acts, via a feedback loop from the retina, to limit the amount of light entering the eye. The normal range of pupil diameters is from 1.5 to 8 mm, which allows

transmission to vary by a factor of 30. There are, however, large variations between observers (Figure 2). The differences result from the fact that pupil size is affected by factors apart from retinal illumination, viz binocular convergence and accommodation (Knoll, 1949; Marg and Morgan, 1949), emotion, drugs and alcohol. Maximum dilation is achievable by the young adult (12-18 years). This ability then decreases with age.

Because pupil size has a significant effect on the optical MTF of the eye (Figure 3), variations in pupil diameter can have a marked influence on total visual performance. A unit of retinal illumination (troland) is used to take account of the influence which the pupil has on the amount of light reaching the retina. One troland is the retinal illumination when the eye views a luminance of 1 Cd m^{-2} through a pupil of area 1 mm^2 . De Groot and Gebhard (1952) proposed an empirical equation relating mean pupil diameter to field (display) luminance.

$$\log d = 0.8558 - \left(4.01 \times 10^{-4} \left[\log \frac{L}{3.183} + 8.1 \right]^3 \right)$$

d is pupil diameter in mm and L is field luminance in Cd m^{-2} . Using this equation, it is possible to plot a curve relating luminance and retinal illumination (Figure 4).

The primary role of the pupil appears to be the protection of the retina against sudden changes in illumination (Woodhouse and Campbell, 1975). Under normal conditions the pupil adopts a size which gives optimum visual resolution (Campbell and Gregory, 1960; Woodhouse, 1975). It should be noted by those wishing to model the visual system, that the efficiency of the retina decreases with increasing angles of incidence. The result is that the effective area of the pupil is smaller than its physical size. This phenomenon is known as the Stiles-Crawford Effect, a good review of which is given by Vos and Walraven (1962).

2.3 The Lens

When it is in a relaxed state, the normal eye is focussed for an object at about arm's length. This 'resting focus' has been studied using bright, empty fields (Schober, 1954; Westheimer, 1957) and also in conditions of darkness (Leibowitz and Owens, 1975a; Johnson, 1976; Owens and Leibowitz, 1980). It also manifests itself in the preferred dioptric setting of optical instruments (Home and Poole, 1977).

Under the action of the ciliary muscles, the crystalline lens allows closer and farther objects to be focussed. For some individuals the eyeball is either longer or shorter than optimum, causing difficulty in focussing far or near objects respectively. This short- or long-sightedness can be corrected by the use of spectacles. The natural range of accommodation decreases with age (Weale, 1963). Table 1 shows the results of a study by Turner (1958).

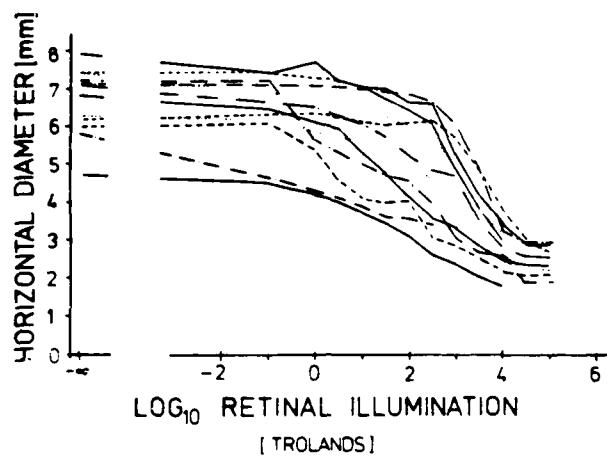


FIG.2 VARIATION OF PUPIL DIAMETER WITH RETINAL ILLUMINATION FOR 12 OBSERVERS

[Adapted from Spring and Stiles, 1948]

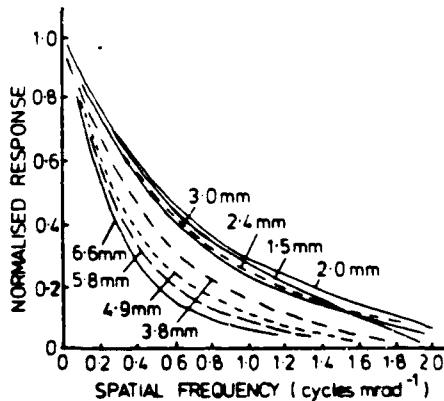


FIG.3 EFFECT OF PUPIL DIAMETER ON THE OPTICAL MODULATION TRANSFER FUNCTION OF THE EYE

[Data from CAMPBELL and GIBSON, 1966]

$$\text{curve A. } \log T = \log L + \delta$$

$$\text{curve B. } \log L = \log T - \delta$$

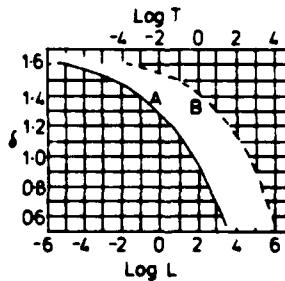


FIG.4 RELATIONSHIP BETWEEN RETINAL ILLUMINATION, T [TROLANDS] AND DISPLAY LUMINANCE, L [Cd m⁻²]

[From the data of deGroot and Gebhart, 1952]

Age Group	Mean value of range (dioptries)	Number of eyes tested
under 13	13.0	78
13-17	10.6	63
18-22	9.5	37
23-27	7.9	45
28-32	6.6	29
33-37	5.8	52
38-42	4.4	53
43-47	2.5	99
48-52	1.6	141
53-57	1.1	155
58-62	0.7	80
63-67	0.6	43
over 67	0.6	37

Table 1. Variation of accommodative range with age

This reduction in accommodative power with age (known as presbyopia) makes it difficult to bring close objects into sharp focus.

Figure 5 shows the effect of defocus on contrast sensitivity. Because defocus causes degradation in visual performance (Campbell and Green, 1965a) it is important to appreciate which factors influence the accuracy of the focussing mechanism. The steady-state accommodation response depends upon the spatial frequency spectrum of the stimulus. The higher spatial frequencies stimulate a more accurate response from the system (Charman and Tucker, 1978a).

Figure 6 shows the typical relationship between the stimulus to accommodation and the visual response. Ideally there should be a one-to-one relationship between the stimulus and the response, but in practice the degree of correspondence depends upon the strength of the stimulus. When the stimulus to accommodation is weak, the actual accommodation is intermediate between resting focus and the stimulus distance. This is a general result which has been obtained under various conditions such as low illumination (Owens and Leibowitz, 1976), instruments with small exit pupils (Leibowitz and Owens, 1975b; Hennessy, 1975), instruments with astigmatic fields (Charman and Whitefoot, 1978) and in situations where binocular convergence did not correspond to the stimulus distance (Burton and Home, 1980). The explanation in each case involves the same basic hypothesis, that if the stimulus to accommodation is weak or confused, then the focussing condition of the eye tends towards the resting focus. For example, a condition known as 'instrument myopia' (short sightedness when viewing through an optical instrument) is the result of a small pupil.

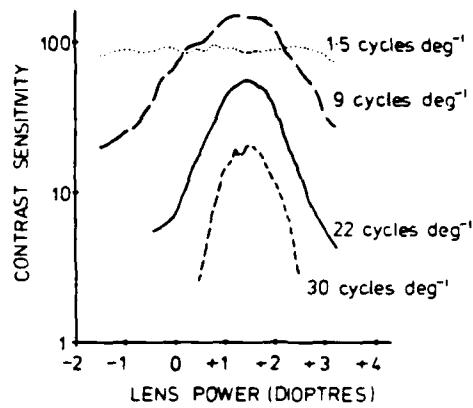


FIG. 5 EFFECT OF DEFOCUS ON CONTRAST SENSITIVITY
TO SINUSOIDAL BAR PATTERNS OF VARIOUS
FREQUENCIES

[After CAMPBELL and GREEN, 1965]

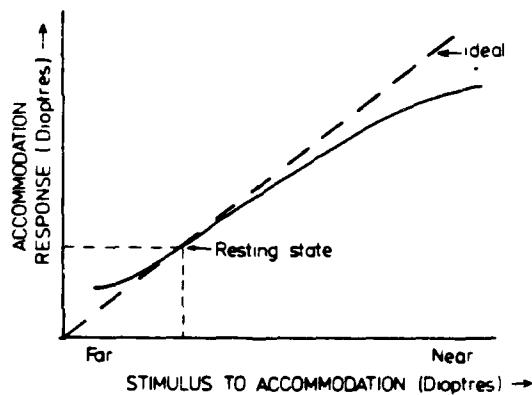


FIG. 6 TYPICAL RELATIONSHIP BETWEEN STIMULUS TO
ACCOMMODATION AND THE PHYSICAL RESPONSE

increasing the depth of focus of the observer's eye. This reduces the requirement for the eye to focus (see Hennessy et al, 1976).

The message to the display engineer would seem to be that he should position a display at about 1 metre + 0.5 m from the user's eyes so that under conditions where the accommodative mechanism is not stimulated strongly, the eye would relax to a position of focus close to the display. When colour displays are used, Charman and Tucker (1978(b)) have shown that trained observers change their level of accommodation, when viewing a target at a constant distance, to compensate for the varying ocular longitudinal chromatic aberration as the colour of the target changes. Untrained observers may respond inconsistently.

2.4 Receptors

Although the ocular media transmit all wavelengths between 380 and 1500 nm (Figure 7), the receptors have a practical operating band of 380 - 770 nm. There are two basic types of receptor in the retina. Rods are the more sensitive receptors and become dominant in night vision. They have a single spectral sensitivity and, as a system, have a coarse spatial response. Cones are less sensitive than rods and are the dominant mechanism for daylight vision. They are predominantly situated within the fovea and provide the basis of high spatial resolution and colour vision. The overall cone response has a peak which is shifted slightly towards the long wavelength (red) end of the spectrum from that of the rod system. Figure 8 shows the spectral responsivities of the two mechanisms.

The spatial distribution of the receptors is shown in Figure 9. The central fovea is rod-free over an area subtending approximately one degree. This is the region upon which is focussed light from the direction of regard (ie when we look at an object we are focussing its image onto the fovea). The foveal cones are approximately matched in size to the smallest point spread function of the optics (viz ~1 min arc). At retinal level, spatial integration increases with angular eccentricity, ie sensitivity is increased at the expense of spatial resolution. At approximately 15 degrees from the fovea on the nasal side of the retina is a blind spot where the nerve fibres leave the retina to enter the nerve sheath (see Figure 1). This blind spot is approximately 3 degrees in diameter.

From Figure 9 it can be seen that during night vision the fovea is effectively blind because it is composed of cones which have low sensitivity. Maximum rod resolution occurs at 15-20 degrees from the fovea, hence the technique of looking away from an object to see it at night.

Cones are present in the retina at large eccentricities. However, it appears that the various colour mechanisms do not all extend to the same angles. For example, Rusis (1966) has found the following angular limits for specific colours.

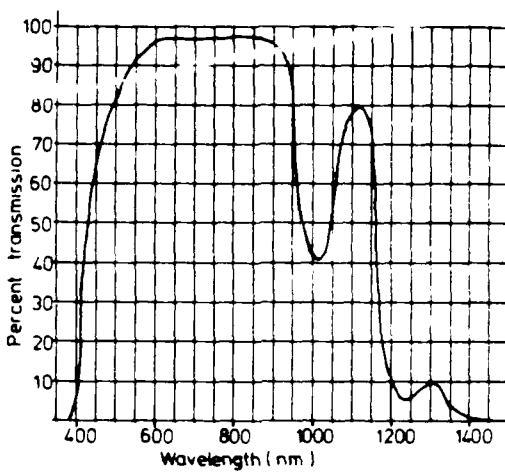


FIG. 7 TRANSMISSION OF LIGHT THROUGH THE OCULAR MEDIA OF THE HUMAN EYE

[AFTER GEERAETS and BERRY (1968)]

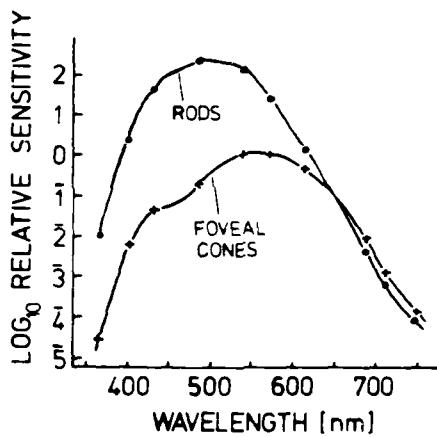


FIG. 8 SPECTRAL SENSITIVITIES OF THE RETINAL RECEPTORS

[From WALD, 1945]

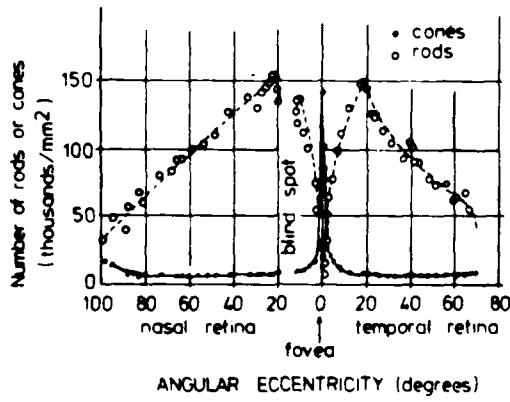


FIG. 9 DISTRIBUTION OF RECEPTORS ACROSS THE HUMAN RETINA

[From ØSTERBERG, 1935]

Colour	Horizontal	Vertical
Green	60°	40°
Red	60°	45°
Blue	100°	80°
Yellow	120°	95°
White	180°	130°

Table 2. Angular limits for several colours

Colour vision is discussed further in section 3.4.

The two kinds of receptor provide the visual system with a wide dynamic operating range. Adaptation of the visual system, from one end of this range to the other, involves a finite period of time. In coming from darkness into light conditions, the rods are paralysed and the cones become effective. Although this change can be physically unpleasant, the process takes a few minutes only. However, the reverse process is much slower. Adapting to darkness may require a period of 45 minutes or more. Figure 10 shows the time course of dark adaptation, which exhibits two distinct portions, being due to the rod and cone functions. A more practical curve is shown as Figure 11. This shows the time required to adapt from bright daylight to a display of variable luminance.

Further details of the adaptive nature of the visual system are given in later sections.

2.5 Binocular Vision

The human binocular structure has several advantages over a monocular system. Firstly, each eye compensates for the blind spot of the other. Secondly, binocular vision provides an accurate means of locating objects in space. Animals have varying degrees of binocular overlap, the predators generally possessing the larger binocular fields (Duke-Elder, 1958). In the human system stereopsis occurs within this region of binocular overlap. Stereopsis is a result of the visual cortex making use of the angular disparities between the two monocular images of a single object. The majority of the visual cortical cells are binocularly activated and are optimally receptive to a particular angular disparity. This optimum disparity varies from cell to cell, indicating a mechanism for encoding objects at different differences (see, for example, Blakemore (1970)). The range of disparities for local stereopsis is less than $\pm 0.5^\circ$ (Sperling, 1970). There is also global stereopsis, which occurs over wide angular fields containing large objects. This is apparently a separate mechanism which makes use of much larger disparities giving completely dissimilar stimuli on the two retinae (Westheimer and Tanzman, 1956; Mitchell, 1969). Thirdly, the two visual channels can provide an increased signal-to-noise ratio, resulting in an increased contrast sensitivity (Campbell and Green, 1965b; Home, 1977). This increase can be greater than that expected from simple probability theory. A binocularly

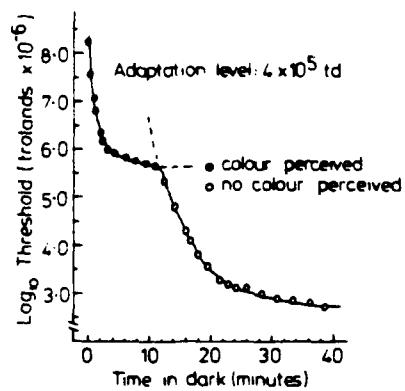


FIG.10 THE TIME-COURSE OF DARK ADAPTATION
 [After HECHT et al., 1937]

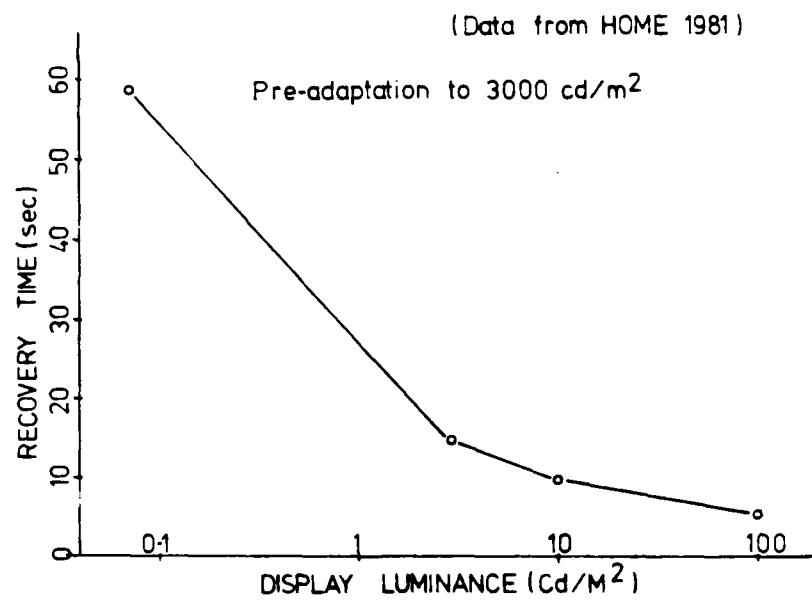


FIG.11 RECOVERY FROM DAYLIGHT TO DISPLAY LUMINANCE LEVELS

activated cell in the visual cortex has a receptive field on the retina of each eye. These binocularly corresponding fields must be stimulated simultaneously to produce the maximum effect in the cortex. Provided that stimuli fall on corresponding receptive fields, maximum binocular sensitivity is the result (Matin, 1962; Thorn and Boynton, 1974). The degree of binocular improvement over monocular vision varies considerably from one observer to another (Home, 1978). Details of the effects of binocular summation on performance are given in Section 3. If the images on the two retinas are not similar or if the binocular disparity increases above the limit of patent stereopsis, binocular rivalry is experienced. Under this condition parts of one image dominate parts of the other, and they alternate dominance in turn (Julesz, 1971).

Psychologically observers prefer to use binocular vision, especially where long viewing periods are involved. However, certain aiming tasks, involving the alignment of two or more stimuli at different ranges, may prompt the use of one eye. This is a technique which can be used to overcome binocular parallax effects.

2.6 Basic Visual Processing

Processing takes place from the receptor stage where the physical layout of the two-dimensional mozaic of rods and cones affects the spatial resolution of the visual system. Beyond the rods and cones, but still at retinal level, there are numerous cells which interact both forwardly and laterally. A general explanation of these cells and their function may be found in Arden (1976). Apart from some spatial integration which increases towards the peripheral retina, it has been shown that there are two types of ganglion cell at retinal level. These have been called X- and Y-cells, which respond with sustained and transient signals respectively. Such cells allow early processing of static and dynamic stimuli.

From the retina a neural representation of the spatial and chromatic characteristics of the physical image is transmitted as a series of frequency modulated pulses along the optic nerve bundle to a body called the lateral geniculate nucleus (LGN). Figure 12 shows the manner in which information arrives at the LGN from the two eyes. Each geniculate cell is driven from a circumscribed retinal region, called the receptive field, and the retina, as a whole, is mapped in a regular manner onto the LGN in the sense that fibres arising close to one another in the retina generally end close together in the LGN. The role of the LGN appears to be the enhancement of the disparity, already present in the retinal ganglion cells, between responses to small centred spots and to diffuse light. Binocular interaction at this level appears to be almost non-existent in primates.

From the LGN information is relayed to the striate cortex. The binocular visual field is mapped onto the cortex in a spatially ordered but distorted manner, the fovea being represented by a disproportionately large area. The striate cortex is organised into columns which measure about 0.5 mm in diameter and extend from the surface to the white matter. The most successful method of investigating responses from single cells is the microelectrode technique where electrical responses are recorded using electrodes having tip diameters measuring less than one micron.

Cells within the LGN and the visual cortex have been classified according to their associated receptive fields. At the LGN receptive fields are concentric, centre-surround, antagonistic regions similar to

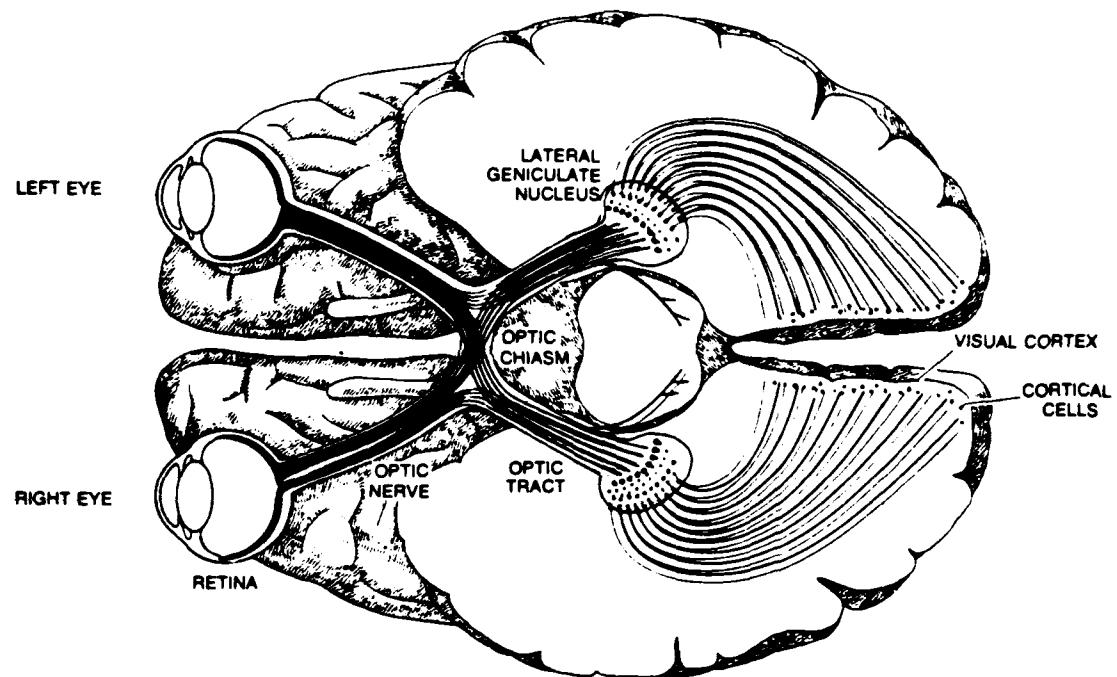


FIG.12 THE VISUAL PATHWAY FROM EYE TO CORTEX

[From PIETIGREW, 1972]

those for retinal ganglion cells. Although cells with such receptive fields have been found at cortical level, the cells within the visual cortex fall mainly into three types called simple, complex and hypercomplex. This classification was suggested by Hubel and Wiesel (1959, 1962, 1968) when recording responses to patterned stimuli from single cortical cells of cat and rhesus monkey. Although Schiller et al (1976a, b) has derived a more detailed classification, the basic cell types are as follows. Simple cells respond best to straight edges, light and dark bars. They seem to respond best to a particular orientation, other orientations producing less vigorous responses, the orientation perpendicular to the optimum generally evoking no response at all. For moving stimuli, certain directions of movement tend to be more effective in producing a response than others. The complex fields are similar insofar as they respond most readily to straight edges and bars but the position of optimally orientated stimuli can vary considerably, the response remaining constant. Further to these, even more specialised cells (hypercomplex) have been observed in cat and monkey cortex by Hubel and Wiesel (1965, 1968). These show optimum response to stimuli limited in length in one or both directions, and also to properly orientated "corners" anywhere in their field.

A small number of single cell recordings have been made from the human cortex of conscious subjects (Marg, 1973). Some receptive fields were circular, some were orientated and most responded to moving stimuli.

There seems to be a divergence of opinion about how colour coding takes place. Motokawa et al (1962) suggested that, to some extent, shape and colour information are transmitted together. However, Andersen et al (1962) concluded that most responses from cortical cells are of narrow spectral band, non-opponent type. More recent work suggests that about 28 per cent of cortical cells are colour-coded (eg Poggio et al, 1971; Dow and Gouras, 1973).

Because we generally perceive a single image of the world about us there must be some mechanism within the cortex whereby the two monocular images are fused. Studying the receptive fields of cat and monkey, Hubel and Wiesel (1962, 1968) concluded that most of the cells in the visual cortex are binocularly activated. The receptive fields of these cells have positional correspondence on the two retinae. Barlow et al (1967) found that for the cat's visual cortex, stimuli correctly located in the visual fields of both eyes were more effective at driving these cells than monocular stimuli and much more effective than a binocular stimulus which was correctly positioned in one eye only. Some binocular cells were found to have an optimum response to stimuli orientated in such a way that their projections onto the retina were at some specific disparity. Support for this was given by Nikara et al (1968). The optimum disparity was found to vary from cell to cell, indicating a mechanism for encoding objects at different distances (Blakemore, 1969, 1970) and different tilts (Blakemore et al, 1972). Thus the cortex uses disparity between the images formed in each eye to give depth perception.

Although much information about movement is processed at retinal level by the X- and Y-type ganglion cells, further processing occurs within the cortex. In primates the extraction of movement information is associated mainly with complex and hypercomplex cells. These span a continuum of spatial and temporal characteristics. In fact, a large

a large majority of cortical cells show directional selectivity and respond optimally to a limited range of target speeds (Movshon, 1974). There must also be feedback from the motor sensory system to enable the visual system to distinguish between target motion within the field of view and target motion across the retina caused by eye movement.

The neurophysiology of the visual system is extremely complex and the literature is vast. Clearly it is not relevant to give more than a very brief summary here. However, the study of how the brain processes visual information and performs such a complex task as recognition is very relevant to those involved in robotic vision. The principle involved within the human visual system is that the various spatial, temporal and chromatic details of a stimulus are processed, if not completely independently, then in a separated manner (parallel processing). A selective convergence of information then occurs to produce a final unitary perception of the visual world. Selective attention can influence the weighting factors associated with each of the converging channels. For example, a search for a circular target amongst many diversely shaped stimuli would involve those possessing sharp corners receiving minimal attention by the visual system. The same argument would apply to a task involving colour selectivity. This selective filtering would necessarily arise from higher levels in the brain and is necessary for optimum processing speed.

Nothing has been mentioned so far about the fact that for higher order tasks such as recognition, a cortical image must exist which can be compared with other images within memory cells. Which attributes of an image are stored for comparison, and the fact that the recognition process seems to be essentially invariant with rotation, translation and size, are factors for future experimentation.

3 MEASUREMENT OF VISUAL PERFORMANCE

The visual system responds to contrast. This can take the form of differences in luminance and wavelength with either position or time. Visual performance varies with overall luminance and Table 3 gives luminance values for some typical visual stimuli. Photopic and scotopic levels refer to conditions under which the visual response is due predominantly to the cones and rods respectively. The mesopic state implies significant responses from both rods and cones. These are general terms and it is difficult to define the point at which one state changes to the next.

3.1 Visual Acuity

Visual acuity is defined as the reciprocal of the angular subtense, in minutes of arc, of the separation which can just be detected between two objects. It is normally measured using high contrast stimuli and because the measured value of acuity is stimulus-dependent it is necessary to define the targets used. Some typical stimuli are shown in Figure 13. For practical purposes 6 metres (20 feet in the USA) is taken as optical infinity for the eye, and photopic distance acuity is usually quoted by clinical opticians with reference to a nominally standard observer. For example, a visual acuity of 6/12 means that the observer is able to resolve at a distance of 6 metres information which a 'normal' observer could resolve at 12 metres. A 'normal' observer is assumed to be able photopically to resolve 1 minute of arc.



FIG.13 TYPICAL ACUITY TARGETS
a-e visual acuity, f vernier acuity

Condition	Luminance(CdM ⁻²)
Sun's surface at noon	10 ¹⁰
	10 ⁹ Damaging
	10 ⁸
	10 ⁷
Tungsten filament	10 ⁶
Aircraft cockpit in sunlight	10 ⁵
White paper in sunlight	10 ⁴ Photopic
	10 ³
Domestic TV screen	10 ²
Confortable reading	10
	1 Mesopic
	10 ⁻¹
White paper in moonlight	10 ⁻²
	10 ⁻³
White paper in starlight	10 ⁻⁴ Scotopic
	10 ⁻⁵
Absolute threshold	10 ⁻⁶

Table 3 Luminance values for typical visual stimuli
(Adapted from Riggs, 1965)

Certain parameters have been shown to affect visual acuity.

a Viewing Distance

Although it has been shown that a change in the distance of a test object from the observer's eye does not bring about an exactly corresponding change in retinal image size (Shlaer et al., 1942) the effect only becomes appreciable at very close range (Hartridge, 1950). This effect occurs because the posterior nodal distance of the eye alters during accommodation and increases the size of the retinal image as the object is brought closer to the eye.

b Ambient Luminance

Visual acuity increases with luminance, becoming virtually constant for ambient luminances above 10 CdM^{-2} (Figure 14). It begins to fall off again at very high levels (above 10^5 CdM^{-2}) as a result of the veiling glare within the eyeball. This only becomes significant when one is considering displays in aircraft cockpits or similar extreme environments. At these levels the luminance of the display must be very high to provide the necessary high levels of contrast, and display glare becomes an important factor also. Methods of improving display contrast are mentioned in Section 4. For normal display conditions the surround illumination should be kept as close as possible to that at the display for optimum visual acuity (Lythgoe, 1932).

c Colour

The eye exhibits significant longitudinal chromatic aberration (Bedford and Wyszecki, 1957). A red image requires about 1 Dioptre of extra accommodation when compared with that required for a blue image (Charman and Tucker, 1978b). This has practical implications for colour displays, especially when highly saturated colours are used. Generally speaking, where monochromatic displays are used to exhibit black on a single-colour background, acuity remains essentially constant with background colour providing luminance is kept constant. The exception to this statement concerns blue light, for which acuity is consistently lower than that with other colours (Shlaer et al., 1942). This is probably due to the fact that there is a lack of blue receptors in the central fovea (see Section 3.4).

d Retinal Position

At high luminance visual acuity decreases into the peripheral retina, reflecting the distribution of cones across the retina. As luminance decreases, so the contribution made by the rods increases until, for ambient luminances of less than about 10^{-3} CdM^{-2} , peripheral acuity is actually higher than that of the fovea (Figure 15). It should be remembered that acuity falls to zero at the blind spot, for all levels of luminance.

e Orientation of the Stimulus

It has long been known that the visual system is sensitive to the orientation of a stimulus. Visual acuity is generally higher for bars orientated vertically or horizontally with respect to a normal upright observer. It is lowest for orientations of 45 degrees from these, and varies fairly smoothly through the intermediate orientations. The effect was thought, originally, to be due to astigmatism in the optics of the eye, but has been shown, by the use of interference fringes, to be a property of the processing mechanism of the visual system (Campbell et al., 1966).

f Binocular Versus Monocular Vision

For people with normal, balanced binocular vision there is a slight improvement in acuity measured binocularly over that measured for one eye alone. The improvement is approximately 7

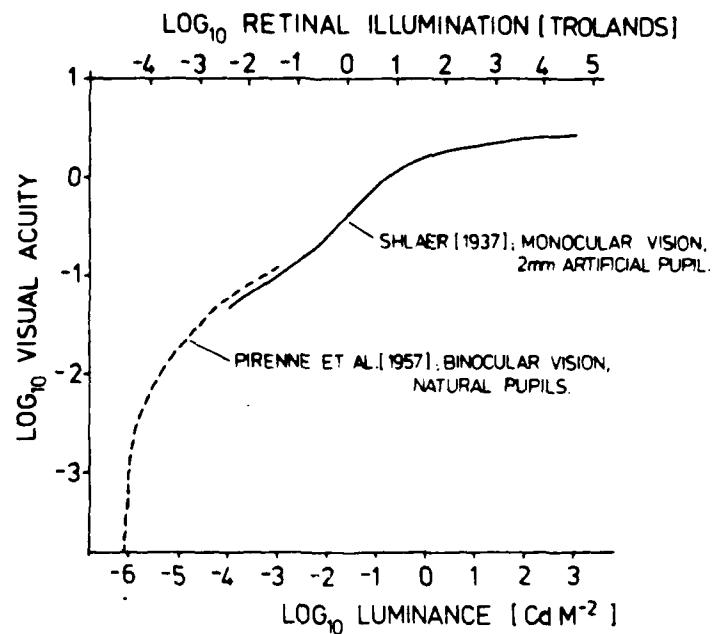


FIG. 14 VARIATION OF VISUAL ACUITY WITH LUMINANCE

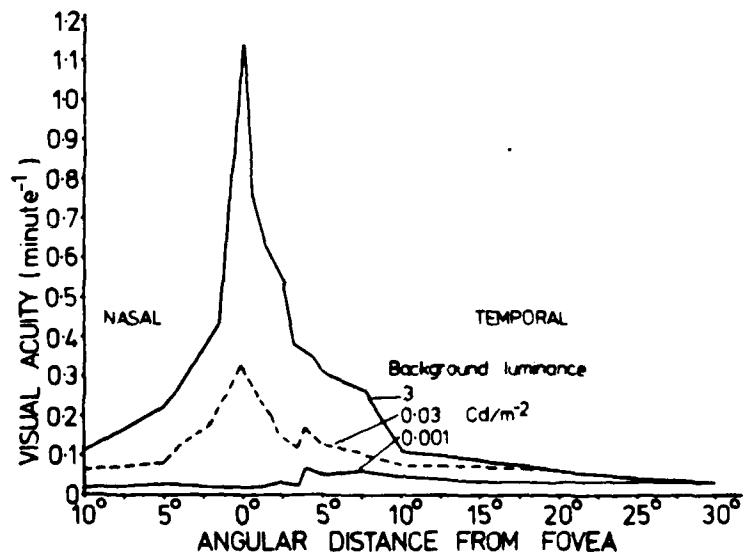


FIG. 15 VARIATION OF VISUAL ACUITY WITH RETINAL POSITION
 [From MANDELBAUM and ROWLAND, 1944]

percent at high luminances (Campbell and Green, 1965; Home, 1978) and probably results from the fact that the binocular vergence mechanism gives a slightly better cue to accommodation, giving an improved image on the retina.

g Motion

If the target moves relatively to the observer, then there is a general reduction in visual acuity. Many measurements have been made of dynamic visual acuity (see for example Ludvigh and Miller, 1958; Burg, 1966; Lavin, 1972), and Figure 16 shows a typical curve.

Another important measurement of visual performance is Vernier Acuity which is the ability of a subject to align two stimuli. Generally, two lines are used as stimuli, and defining vernier acuity as the reciprocal of the standard deviation (in seconds of arc) of the error in setting the two lines colinear, measured thresholds have ranged between 0.5 and 12 seconds of arc (Walls, 1943). Line length affects the measurement of vernier acuity (Foley-Fisher, 1973), a minimum value being obtained using line lengths of about 1 degree at the eye. Optimum performance is achieved with line widths of about 15 minutes of arc. High contrasts and steep edge gradients produce the best results (Foley-Fisher, 1977). A related measurement is stereo-acuity which is covered in Section 3.3.3.

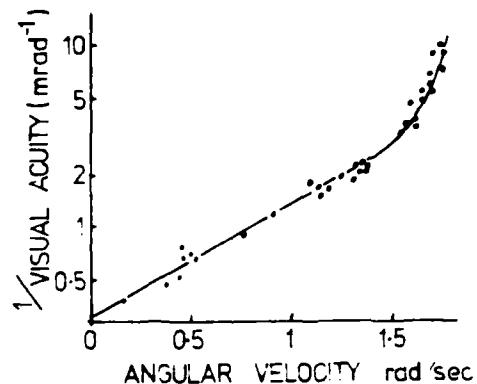
Visual acuity is a gross measure of the spatial resolution of the visual system, and reflects the limitations imposed by the receptor sizes and distributions, spherical and chromatic aberration in the optics of the eye, and diffraction at the iris. It gives very little indication of the higher order processes which occur at and beyond the retina.

3.2 Contrast Sensitivity

Measurement of visual contrast threshold has been used widely to determine the response characteristics of the visual system. Contrast sensitivity is normally defined as reciprocal contrast threshold. The definition of contrast depends on the type of stimulus presented to the eye. Various stimuli are used to measure contrast sensitivity and broadly there are two approaches used by vision researchers.

3.2.1 Isolated Stimuli

Historically, the isolated target against a uniformly illuminated background was used consistently for many years until the idea of applying linear systems analysis took hold in the 1960s. For an isolated stimulus, contrast is usually defined as $(L_1 - L_2)/L_2$, where L_1 and L_2 are the luminances of the target and background respectively. Although many experimentalists have used the single target approach, Blackwell (1946) carried out a mammoth study which has been used as the basis of many vision models and is frequently quoted as the authority on basic contrast discrimination. Blackwell carried out measurements of threshold contrast (using a two-alternative, forced-choice technique) for a wide range of light levels and target sizes. The results can be represented in various ways, and Figures 17 and 18 give two examples. Other researchers have found it difficult to duplicate the very low thresholds reported by Blackwell (eg Vos et al, 1956), but his results can be taken as optimum values for most practical purposes.



(From Lavin, 1972)

FIG. 16 EFFECT OF MOTION ON VISUAL ACUITY

[From LAVIN, 1972]

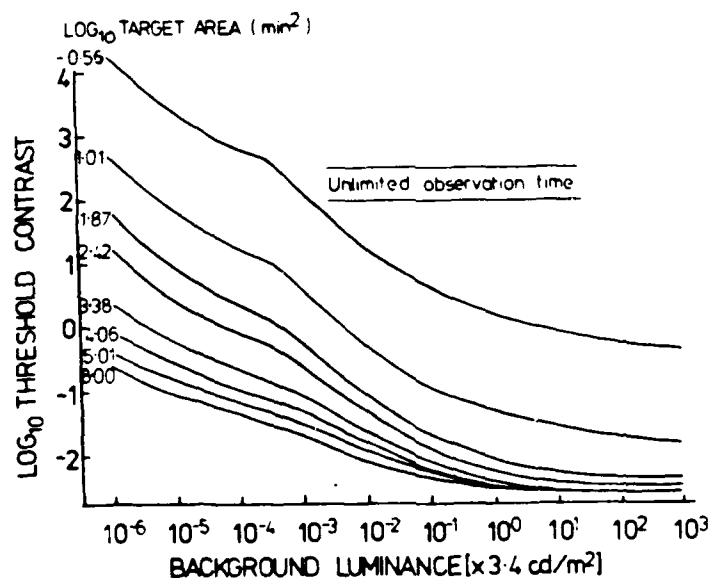


FIG. 17 VARIATION OF THRESHOLD CONTRAST
WITH LUMINANCE

[From BLACKWELL, 1946]

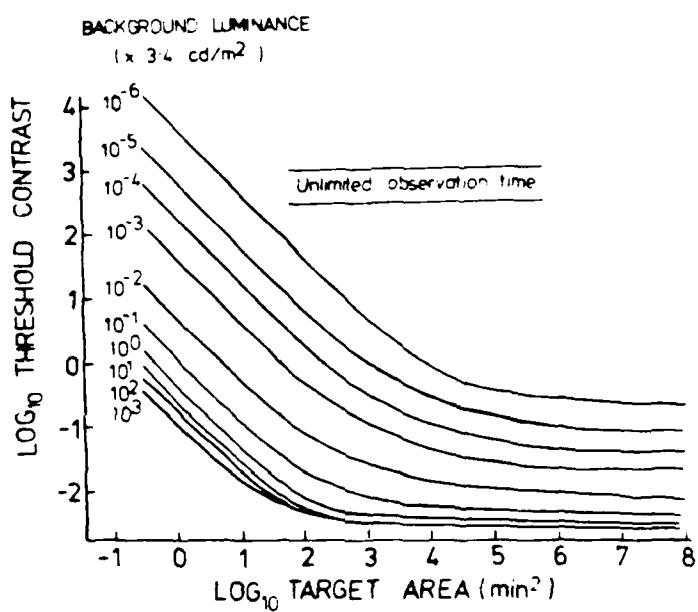


FIG. 18 VARIATION OF THRESHOLD CONTRAST WITH TARGET SIZE

[From BLACKWELL, 1946]

The effect of the size of a stimulus on its detectability can be summarised by 3 distinct relationships, which are important for modelling purposes.

a For very small objects, centred on the fovea, there is complete summation of incident flux. The result is Ricco's law which states that

$$I_a^2 = \text{Constant}$$

where I is the threshold intensity and a is the angular subtense of the stimulus. This can be written in terms of contrast. Ricco's law holds for stimuli subtending small visual angles (typically $a \leq 10$ minutes of arc) at the fovea, and up to 1 degree in the periphery (Sakitt, 1971).

b For objects subtending angles greater than 10 minutes of arc and less than 2 degrees, Piper's law applies

$$I_a = \text{constant}$$

c The relationship reduces to

$$I = \text{constant}$$

for all sizes of stimulus greater than approximately 2 degrees.

Contrast sensitivity varies across the retina (Figure 19) reflecting the relative distributions of rods and cones and the fact that in the peripheral retina there is a high degree of spatial interaction between rods particularly, which enhances sensitivity at low luminances.

Both shape and edge-blur can effect detectability of a stimulus. Increasing aspect ratio gives rise to an increase in threshold contrast for a given target area (Figure 20). Edge-blur also results in a decrease in target detectability (Figure 21) and edge-effects generally constitute a very important aspect of the visual system. The presence of an edge-enhancement mechanism within the system gives rise to an effect known as Mach-banding. This is the visual brightness distribution which is sometimes evident at an abrupt change in luminance gradient. The effect is illustrated graphically in Figure 22.

At daylight levels of illumination there is a ratio of approximately $\sqrt{2}$ between binocular and monocular sensitivity to contrast (Crozier and Holway, 1939; Kristofferson, 1958), and the ratio is maximal when binocular convergence is correct for a given stimulus distance. This fact is particularly important for binocular instrument design, and Figure 23 shows the result of a study by Burton and Home (1980). The improvement ratio has been explained in terms of a signal-to-noise ratio in two independent channels. However, the figure, $\sqrt{2}$, should be taken as an approximate factor only. It can vary markedly from one person to another, and can increase to values of 1.6 or greater under lower luminance conditions (Home, 1978).

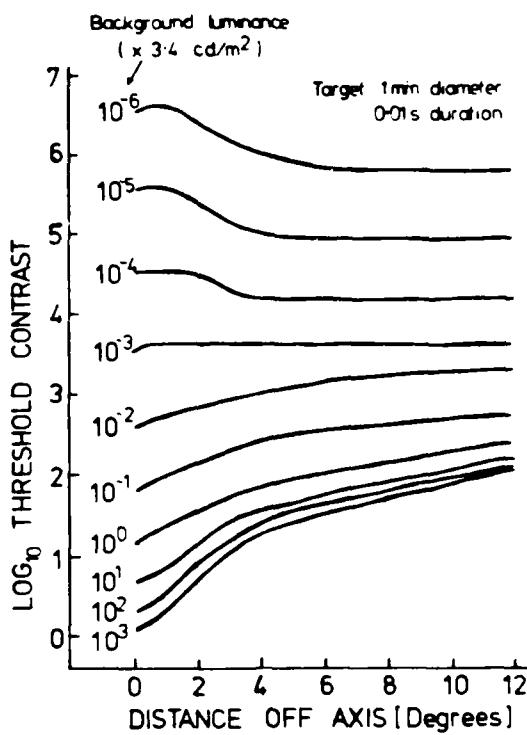


FIG. 19 VARIATION OF THRESHOLD CONTRAST WITH RETINAL POSITION

[From BLACKWELL and TAYLOR, 1969]

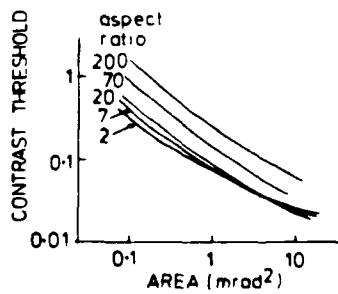


FIG. 20 EFFECT OF STIMULUS SHAPE ON CONTRAST THRESHOLD

[From LAMAR et al, 1948]

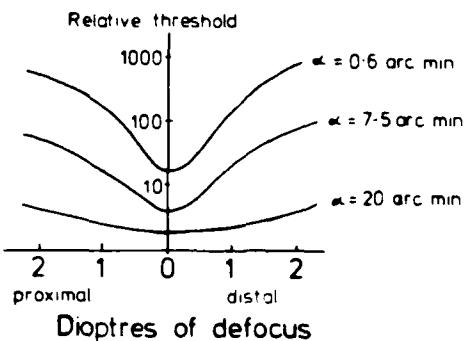


FIG. 21 EFFECT OF DEFOCUS BLUR ON DETECTION THRESHOLDS OF DISC STIMULI OF ANGULAR DIAMETER, α

[Adapted from OGLE, 1961]

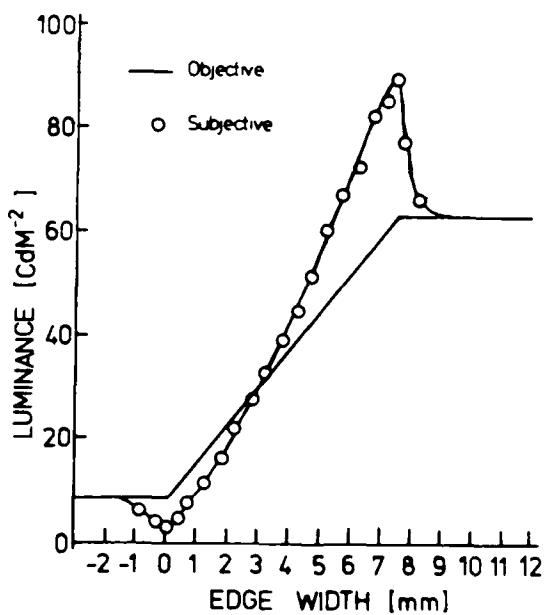


FIG. 22 ENHANCEMENT OF PERCEIVED EDGES (MACH BANDS)

[From LOWRY and DEPALMA, 1961]

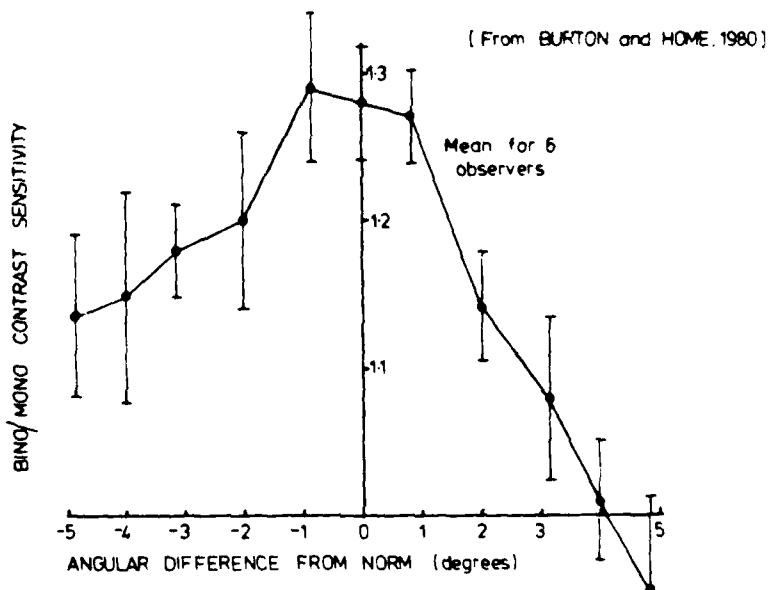


FIG.23 EFFECT OF BINOCULAR VERGENCE ON BINOCULAR SUMMATION

3.2.2 Extended Targets - Grating Stimuli

The last 25 years have seen the introduction of experiments based on an assumption that the visual system can be described on a linear systems analogy. Contrast sensitivity is measured using gratings with sinusoidal luminance distributions, the hope being that some fundamental properties of spatial vision will emerge. A linear system is assumed to be valid for small signal amplitudes and contrast sensitivity measured as a function of spatial frequency is often equated to the modulation transfer function (MTF) of the visual system. Its basic shape is that of a pass-band filter which changes with mean luminance (Figure 24) and retinal position (Figure 25).

Within the overall pass-band it has been hypothesised that the visual system comprises multiple channels, each of which responds optimally to a specific spatial frequency band (Sachs et al, 1971; Hauske et al, 1976). The bandwidth of an individual channel is typically 1 - 1.5 octaves and the contrast sensitivity function is assumed to result from many such channels, the shapes and bandwidths of which are based on both psychological and physiological data. Figure 26 shows how the selective channels give rise to a band-pass sensitivity function.

Contrast sensitivity varies across the retina as a function of spatial frequency (Rijssdijk et al, 1980; Kroon et al, 1980), and because probability summation occurs across space for an extended target such as a grating (King-Smith and Kulikowski, 1975; Robson and Graham, 1981), many experimentalists have used targets with triphasic spatial profiles (Figure 27) to localise both target position and spatial frequency.

Support for the multiple channel theory of vision is given by the phenomenon of spatial-frequency masking (Stromeyer and Julesz, 1972). When the eye has adapted to a grating of given spatial-frequency, there is a subsequent decrease in contrast sensitivity over a band of frequencies centred on the adaptation frequency. This means that visible noise or even background structure can effectively mask displayed images, particularly where critical information is close to threshold.

Some further general properties of the contrast sensitivity function are that it varies with orientation (Figure 28), display size (Figure 29) and whether observations are made monocularly or binocularly, the improvement in sensitivity for binocular vision being approximately $\sqrt{2}$ for high luminances (Campbell and Green, 1965b).

3.2.3 Suprathreshold Contrast Discrimination

Although measurements of contrast threshold have revealed a great deal about the underlying mechanisms of visual perception, it is difficult to apply such data to the viewing of everyday scenes. Because differences in brightness are what enable us to perceive structure in real scenes, the measurement of perceivable differences in brightness is important for modelling practical systems. The general form of the visual response function is:

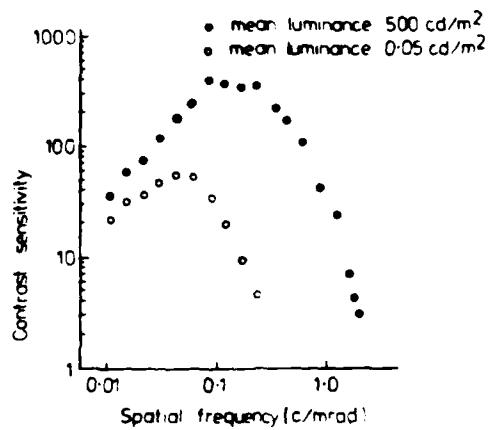


FIG. 24 THE CONTRAST SENSITIVITY FUNCTION FOR SINE-WAVE GRATINGS

[From CAMPBELL and ROBSON, 1968]

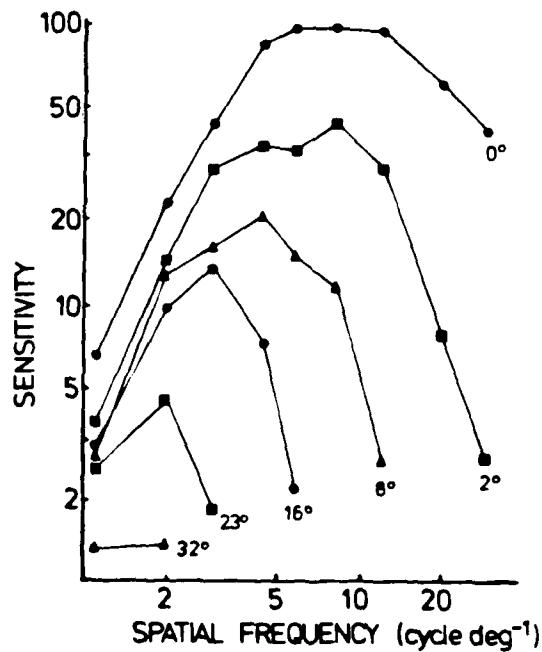


FIG. 25 VARIATION OF CONTRAST SENSITIVITY FUNCTION WITH RETINAL ECCENTRICITY IN THE TEMPORAL FIELD USING A 2.45° STIMULUS

[From HILZ and CAVONIUS, 1974]

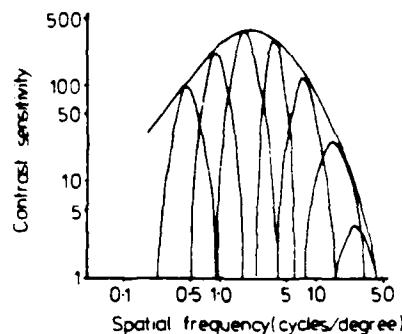


FIG. 26 REPRESENTATION OF SPATIAL FREQUENCY CHANNELS WHICH MAKE UP THE CONTRAST SENSITIVITY FUNCTION

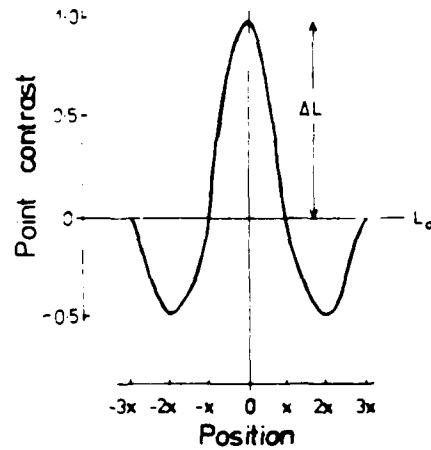


FIG. 27 POSITION CONTRAST PROFILE OF THE TRIPHASIC STIMULUS USED BY BURTON (1981) TO GIVE LOCALISATION OF BOTH POSITION AND SPATIAL FREQUENCY. STIMULUS CONTRAST IS DEFINED AS ΔL/L_0, WHERE L_0 IS BACKGROUND LUMINANCE.

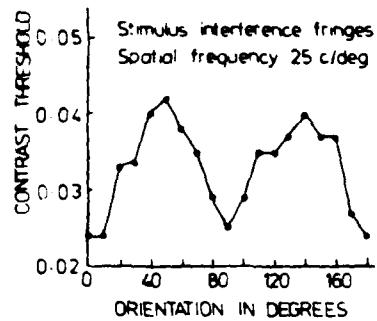


FIG. 28 VARIATION OF CONTRAST THRESHOLD WITH
ORIENTATION OF THE TEST PATTERN
[From CAMPBELL et al, 1966]

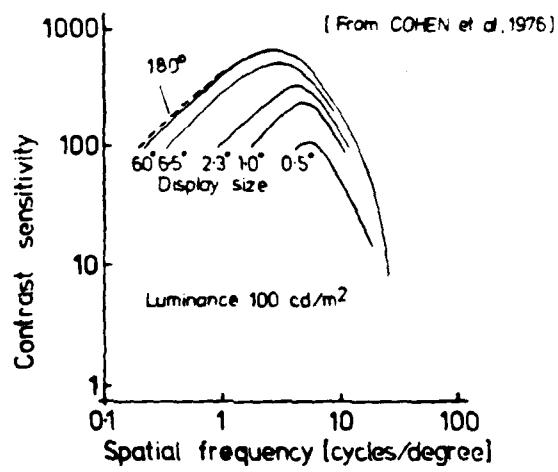


FIG. 29 EFFECT OF DISPLAY SIZE ON CONTRAST
SENSITIVITY OF THE EYE

$$\Delta B = kB^n$$

where ΔB is the change in brightness which is just discernible from a background adapting brightness of B . k is a constant and n is a variable which depends on the conditions imposed. For high (photopic) light levels and long duration stimuli ($t > 1\text{sec}$) $n = 1$ and we are left with

$$\Delta B = kB$$

which is known as the Weber-Fechner law, and suggests that the signal transfer function is logarithmic. This relationship can also be written in terms of contrast, ie

$$\Delta C = wC$$

and taking a frequency-averaged value of 0.08 for w , Burton (1981) has shown that the transfer function becomes less frequency-selective as contrast increases. He has also calculated the number of discriminable contrast steps as a function of spatial frequency (Figure 30) which is directly applicable to display design. His results give experimental support to the theoretical calculations of Mezrich et al (1977).

Rose (1942, 1948) and DeVries (1943) have proposed that visual performance is determined by statistical fluctuations in quantal absorption. The result is the Rose-DeVries law:

$$\Delta B = kB^{\frac{1}{n}}$$

which seems to hold approximately for short-duration, small-area stimuli (Barlow, 1957). Between the two extremes of the Weber-Fechner law and the Rose-DeVries law, one would expect n to vary between 0.5 and 1.0. This has been demonstrated experimentally by Legge (1981).

When different spatial frequencies are compared visually, it is found that contrasts can be matched largely independently of luminance and retinal position. This is thought to be made possible by a neural "deblurring" mechanism which optimises clarity of vision by compensating for earlier attenuation (Georges and Sullivan, 1975).

3.3 Form Perception

3.3.1 General Shape Recognition

Although many researchers have attempted to quantify form perception, very little success has been achieved in arriving at a general theory. The most general model must necessarily involve the effects of past experience which is extremely difficult to define, and even more difficult to quantify mathematically. Zusne (1970) attempted to list several classifications of form perception in both military and industrial situations. Three types of noise were defined.

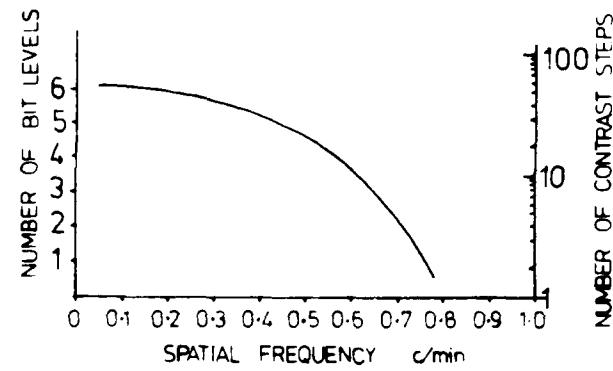


FIG. 30 MINIMUM NUMBER OF GREY LEVELS REQUIRED
TO DISPLAY DIFFERENT SPATIAL FREQUENCIES

[From BURTON, 1981]

- a Noiseless: A stimulus stands out from its immediate background. Eg instruments and scales.
- b Organised noise: Target blends into its background with contours ill-defined. Eg military vehicle painted with contour camouflage patterns.
- c Random noise: Target obscured by noise in background (clutter). Eg small vehicle viewed in rocky terrain.

When displays are used to present a target and background then further noise effects, due to the display itself, are involved. In such a situation it is usually more convenient to divide noise further into target-related and display-related (or system-related) effects. It is possible to treat the entire subject of visual perception with displays as signal-to-noise discrimination (Biberman, 1973). A limited description of the effects of noise on visual perception is given in Section 3.6.

Studies of form perception appear under numerous descriptors such as:

- Form discrimination
- Shape and size discrimination
- Feature extraction
- Contour/profile analysis
- Recognition

An early study by Helson and Fehrer (1932) considered the recognition of simple shapes such as discs, rectangles and triangles. Casperson (1950) used thirty simple shapes for a form discrimination task and concluded that there was no common discriminatory behaviour for the different forms. Brown (1972) extended the approach to simple stylised shapes which could be divided into simple, resolvable building blocks - an elementary "feature extraction" approach. Further to this, studies have been carried out at British Aerospace (Seale, 1973; Clare, 1975 ; Brown and Clare, 1975) with military and non-military (bush) targets, using a Repertory Grid Technique (Kelly, 1955; Bannister and Mair, 1968) to identify the features of importance in recognising military targets. The results showed that there were some common features used to distinguish the targets, and also that edge gradients may be important in perceptually defining the target.

In general, the results of studies of visual form perception seem to be very stimulus-dependent. Global theories are difficult to formulate, except perhaps that for silhouette targets some features are more important than others, depending on the set of stimuli used.

There are two main modelling approaches in use at present. The BAe ORACLE model (Overington, 1977) which is based on contour discrimination, and the NVEOL model which is based on Johnson criteria. These relate recognition and identification to a process in which a signal is detected against a noisy background (Johnson, 1958). Both approaches have had success with particular types of imagery, although further sophistication is necessary before the modelling can be usefully applied to machine recognition.

3.3.2 Visual Illusions

The visual processing of suprathreshold information does involve some penalties. In Section 2.6 it was explained that within the visual cortex lines and corners assume a special significance. It is also true that the eye looks for continuous lines and closed contours, the nett result of which can be illusions caused by the inference of lines or contours where physically none exist. Figure 31 shows a typical example where the observer sees a triangle whose vertices are bounded by the removed sectors of the black discs. Clearly, no such physical triangle actually exists. Other illusions affect the visual judgement of straightness, parallelness and equality of length, and it is important that the display engineer be aware of such limitations of the visual system. Some examples are shown in Figure 32. The topic is treated in depth by Gregory (1966).

3.3.3 Binocular Perception

Apart from the slight improvement in acuity, and a 40 to 60 percent increase in contrast sensitivity, the main advantage of binocular over monocular vision is stereopsis. When the two eyes view a real object in three dimensions, the retinal images are different because of their 6 to 7 centimetres separation. Providing that the two images fall on corresponding areas, the cortex can correlate the disparities and the result is depth perception (or stereopsis). Stereoscopic acuity (Figure 33) is typically 5 seconds of arc (Solomons, 1978) implying that for the unaided eye stereoscopic vision only becomes effective for target ranges of less than 450 - 500 metres (Graham, 1951).

Binocular depth perception is a relatively early visual process, using point-by-point or feature-by-feature comparisons between left and right fields. The two eyes are positioned by a muscular mechanism linked to the accommodation mechanism of the lens. For normal situations this reflex vergence movement minimises the retinal disparities until single binocular perception is attained. If, for some reason, retinal disparities cannot be reduced sufficiently (ie the two images cannot be correlated) then diplopia (a double image) may be perceived. Such a situation is not acceptable to the visual system for very long, and retinal rivalry results.

In general, when different images fall on corresponding regions of the two retinae, the cortex suppresses the image from one eye in favour of the other. The result is a single monocular image. Approximately 97 percent of the population show a consistent preference for one eye (Crider, 1944) and the tendency is for the image from this eye to be accepted in preference to the other. In cases of strabismus (squint) at birth, the input to the cortex from the

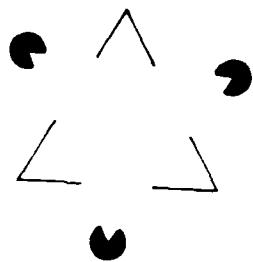


FIG. 31 ILLUSORY TRIANGLE PERCEIVED WHERE PHYSICALLY NONE EXISTS

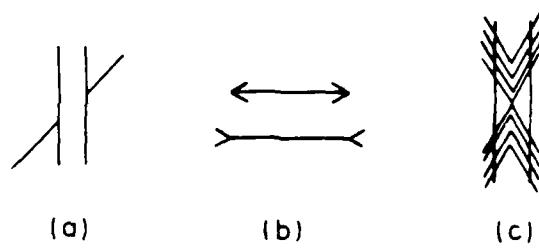


FIG. 32 EXAMPLES OF SIMPLE VISUAL ILLUSIONS

- (a) oblique lines appear not colinear
- (b) horizontal line lengths appear unequal
- (c) vertical lines appear non-parallel

dominant eye may completely swamp that from the other eye and the processing mechanisms for that eye may be permanently impaired. Such a condition is termed amblyopia.

Retinal rivalry does not always give rise to complete suppression of one monocular channel, and dominance of the eyes can vary over the retinae. More generally, the perceived image alternates between that produced by the left eye and that produced by the right eye, with shorter periods during which both images can be seen at once. A number of studies have been carried out using grating targets, the results of which show that the dominant eye tends to prevail for a longer total time period during binocular rivalry (Porac and Coren, 1978). Differences in colour between the two monocular images, and differences in orientation result in different rates of alternation (Thomas, 1978), a larger difference in orientation producing a higher rate of alternation. A study by Fahle (1982) showed that a decrease in contrast and/or spatial frequency content reduced predominance during rivalry. This result was shown to apply to both periodic and aperiodic stimuli. Broader reviews of binocular rivalry have been given by Levelt (1968) and Laycock (1976).

3.4 Colour Vision

3.4.1 Trichromatic Principles

The appearance of coloured stimuli can be described in terms of three psychological attributes.

a Hue

This is the dimension generally referred to by the colour names red, yellow, green, blue etc. The most closely related physical quantity is wavelength.

b Saturation

This is the vividness or purity of a colour. A colour can be desaturated by mixing it with white light. The most closely related physical quantity is excitation purity.

c Brightness

This is the attribute which relates to the quantity of radiation affecting the eye. It changes as physical intensity.

In a colour-matching task the eye is trichromatic. This means that a given colour can be matched visually by a mixture of three primary colours. Wald (1964) has even suggested that the retina possesses three classes of cone, with peak absorptions at approximately 440, 525 and 562 nm, although this is probably an oversimplification, because in practice, it has proved to be impossible to measure three unique cone response functions. In the absence of three such response curves which could be used to put human colour vision on a completely physical basis, the Commission Internationale de l'Eclairage (CIE) agreed, in 1931, upon a set of three

colour-matching functions which would enable human colour vision to be represented vectorially. The functions, which represent colours which are more saturated than physically realisable ones, are chosen so that colours can be matched without the necessity of using negative quantities. It should be remembered however, that the CIE colour-matching functions represent centrally-fixated stimuli of two degrees subtense. Accepting their limitations, the matching functions can be used to produce a standardised vectorial representation of colour vision.

Figure 34 shows the wavelength distributions of the CIE colour-matching functions x_i , y_i and z_i . The dependent variable of each function is called the 'tristimulus value'. The numerical values can be found in Wyszecki and Stiles (1967). The y curve is identical to the relative luminescent efficiency function (see Figure 8).

Using the standard matching functions it is now possible to represent any coloured stimulus on what is known as a chromaticity diagram, as follows. If the spectral energy distribution of the stimulus is E_i , specified at intervals of wavelength, λ_i , then the tristimulus values X , Y and Z are calculated from

$$\begin{aligned} X &= \sum a\bar{x}_i E_i \lambda_i \\ Y &= \sum a\bar{y}_i E_i \lambda_i \\ Z &= \sum a\bar{z}_i E_i \lambda_i \end{aligned}$$

Strictly speaking, these relationships should be written in the form of integrals. In practice λ is 10 nm for x , y and z (sometimes interpolated to 5 nm) so it is realistic to use simple summation.

If the units are chosen so that $a\bar{z}_i = 1$ then the relationships reduce to

$$\begin{aligned} X &= \sum \bar{x}_i E_i \\ Y &= \sum \bar{y}_i E_i \\ Z &= \sum \bar{z}_i E_i \end{aligned}$$

It is now clear that

$$\frac{X}{X} = \frac{Y}{Y} = \frac{Z}{Z} = \frac{1}{X+Y+Z}$$

where x , y and z are the relative amounts of the primaries necessary to match the original stimulus. The relationships can be written as

$$\begin{aligned} x &= \frac{X}{X+Y+Z} \\ y &= \frac{Y}{X+Y+Z} \\ z &= \frac{Z}{X+Y+Z} \end{aligned}$$

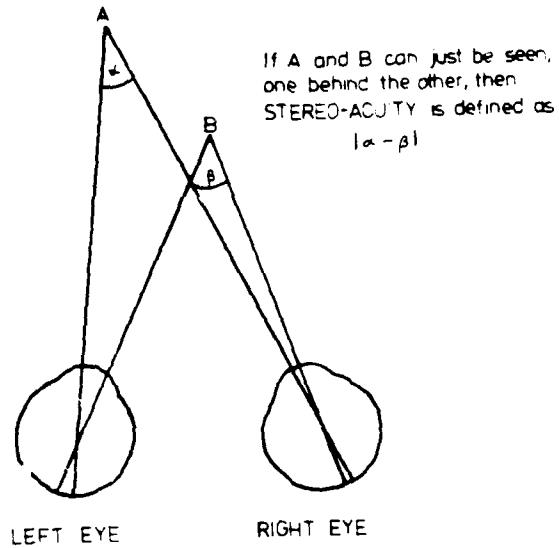


FIG. 33 DEFINITION OF STEREO-ACUITY

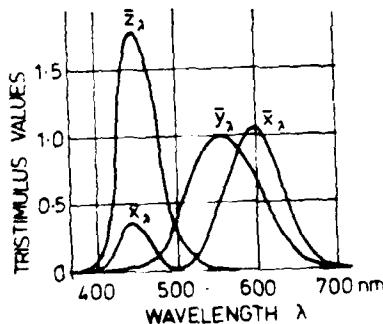


FIG. 34 1931 CIE COLOUR-MATCHING FUNCTIONS
 [From WYSZECKI and STILES, 1967]

and since $x + y + z = 1$, it is possible to plot the stimulus in two-dimensional space (Figure 35), the resulting representation being called the 'CIE chromaticity diagram'. The salient features of the diagram are as follows.

The spectrum locus is represented by the triangular-shaped curve. This depicts colours which cannot be distinguished from monochromatic stimuli of the wavelengths indicated. Colours inside the bounds of the spectrum locus are desaturated, the point, E, representing equi-energy white ($x = y = 0.33$). A line drawn from E, through a colour, C, cuts the locus at the point W, which is the dominant wavelength (Figure 36). The straight-line part of the locus, joining the red to the blue colours, represents the non-spectral purples (mixtures of red and blue). Brightness must be represented in a third dimension, although unfortunately it is not independent of the other two dimensions, there being hue shifts with changes in brightness (Newhall et al., 1943). A mixture of two colours on the chromaticity diagram will appear on the straight line joining the two. The exact position depends on the relative intensities.

Although discriminable differences in physical wavelength can be measured (Figure 37) it is possible to show on the chromaticity diagram the limits of discrimination in both hue and saturation. MacAdam (1942) measured sensitivities to differences in hue and saturation, and his results are shown in Figure 38. It can be seen that discrimination loci are elliptical in shape. Both size and shape vary across the diagram, which means that equal separations on the CIE chromaticity diagram do not indicate equally discriminable differences in hue or saturation. It is possible to perform a mathematical transformation on the diagram so that the MacAdam ellipses are approximately circular. The new diagram is called the CIE (1960) Uniform Colour Scale (UCS) and the transformed values of x , y and z are designated u , v and w (Figure 39) where

$$\begin{aligned} u &= \frac{4x}{-2x + 12y + 3} \\ v &= \frac{6y}{-2x + 12y + 3} \\ w &= \frac{3y - 3x + 1.5}{6y - x + 1.5} \end{aligned}$$

From Figure 39 it can be seen that the MacAdam's ellipses are not transformed to exactly equal circles, but they are certainly more equal in area than those plotted in x, y coordinates.

One practical limitation of the resultant colour-space is that reds, oranges and yellows occupy a relatively small area of the diagram. Because of the industrial importance of such colours, the CIE recommended a further transformation (1976) to expand this region of the UCS diagram. The transformation is

$$\begin{aligned} u' &= u \\ v' &= \frac{3v}{2} \end{aligned}$$

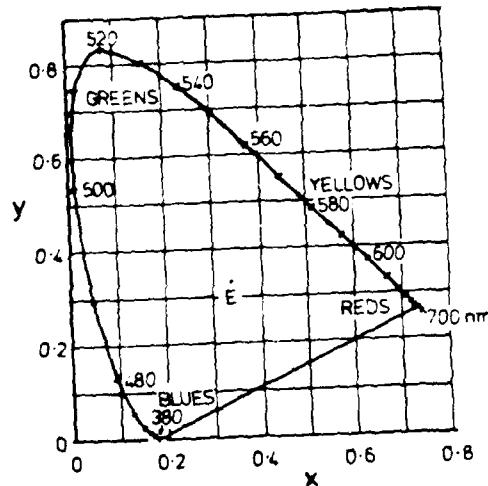


FIG 35. 1931 CIE [x,y] CHROMATICITY DIAGRAM SHOWING THE SPECTRUM LOCUS AND EQUAL-ENERGY STIMULUS E.

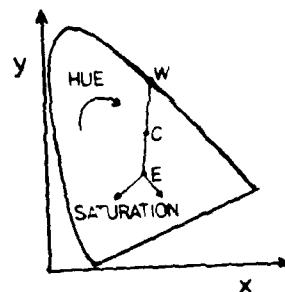


FIG 36. CIE CHROMATICITY DIAGRAM SHOWING DIMENSIONS OF HUE AND SATURATION

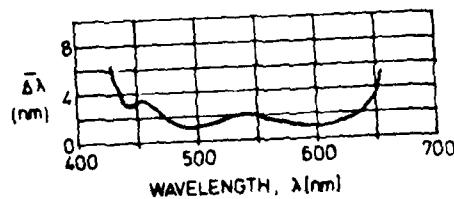


FIG. 37 WAVELENGTH DISCRIMINATION CURVE FROM THE DATA OF WRIGHT AND PITT (1934)

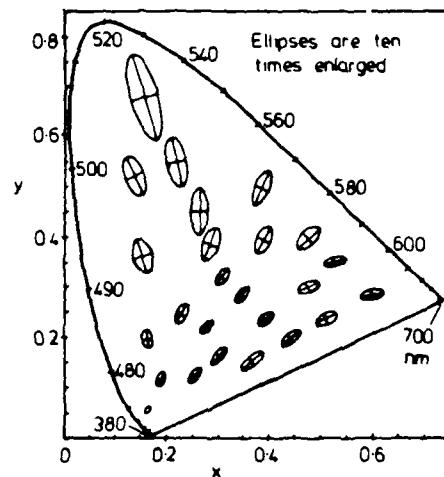


FIG. 38 MACADAM'S COLOUR DISCRIMINATION ELLIPSES WHICH SHOW THE LOCI OF THE STANDARD DEVIATIONS OF COLOUR MATCHES ABOUT THE ELLIPSE CENTRES

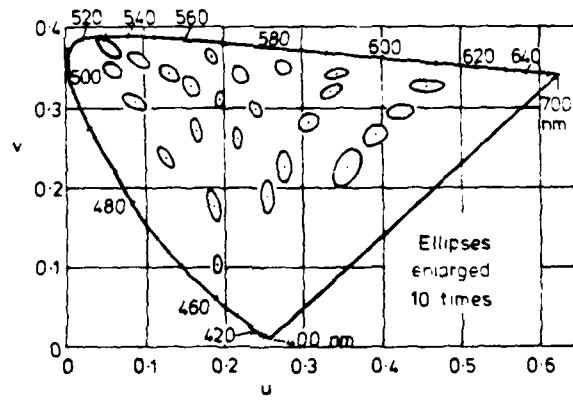


FIG. 39 1960 CIE-UCS DIAGRAM SHOWING THE TRANSFORMED MACADAM'S ELLIPSES

A good explanation of practical applications of the various colour scales to display technology is given by Laycock and Viveash (1981).

3.4.2 Colour Vision in Practical Situations

Providing that conditions are close to those which apply to the CIE chromaticity diagram then it is possible to model colour vision in a reasonably predictable manner. However, in many practical environments conditions are far removed from the two-degrees, foveal-viewing situation. This section describes some of the known effects which apply to colour vision in practical situations.

Intensity

The intensity of a coloured stimulus can effect its hue. This is known as the Bezold-Brücke Effect (Purdy, 1931) and causes high intensity reds and greens to look more yellowish, and causes blue-greens and violets to look bluer (Figure 40).

Stimulus size

Generally speaking, as a stimulus becomes larger so the perceived colour looks brighter. Very small stimuli can give rise to tritanopia (Section 3.4.3) and perception can become essentially achromatic (Rusis, 1966).

Colour Contrast

Colour changes can occur as a result of colour contrast between adjacent stimuli. For example, if a highly saturated colour is located next to a weakly saturated colour of the same hue, then the stimulus of high saturation appears even more saturated than if the two stimuli had been presented individually. The weakly saturated colour may appear achromatic or even of complementary hue to the more saturated stimulus. Adjacent stimuli of complementary hues appear more saturated than if they were viewed on their own. Sharp contours between adjacent coloured regions enhance saturation and brightness. High brightness contrast tends to reduce apparent hue contrast. It is also interesting to note that the visual colour system exhibits what is called 'colour constancy'. This is the phenomenon whereby colour differences are preserved under various illuminants. That is, a red apple against green foliage will still appear to be a red apple against green foliage if viewed through an orange filter. The mechanism seems to be such that relative distances on the chromaticity diagram are kept constant after a transformation of the axes, account of which is taken in the visual cortex. The constancy is not perfect and usually requires a few minutes of adaptation.

Colour Latency

The different foveal colour mechanisms have different integration times, ranging from approximately 50 ms for the red, to 200 ms for the blue, with the green having a time between the two (Burnham et al, 1963). The peripheral retina, however, is more sensitive to red and blue than to green, but response times for red are greater than those for blue or green (Haines, 1975). This complicated behaviour of the

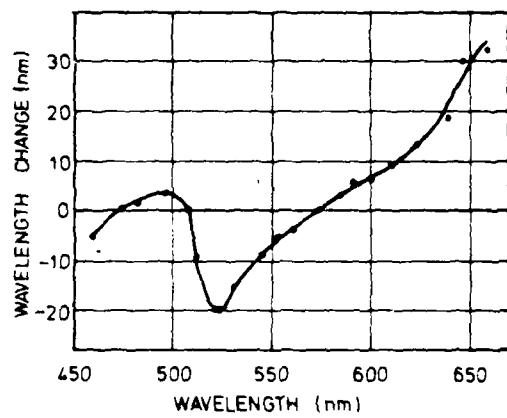


FIG. 40 BEZOLD-BRÜCKE EFFECT
THE DATA SHOW THE CHANGE IN
WAVELENGTH PRODUCING THE SAME
CHANGE OF HUE AS AN INCREASE OF
RETINAL ILLUMINANCE FROM 100 TO
1000 TROLANDS.

[Data abstracted from PURDY, 1931]

colour mechanisms cannot be described simply and a display designer wishing to make use of colour stimuli falling on the peripheral retina would be well advised to read Haines (1975) who considers the topic in depth.

Peripheral colour vision

The different colour mechanisms do not extend into the peripheral retina to the same degree (see Table 2). One effect is that colour discrimination becomes worse as a stimulus is moved away from the fovea (Weale, 1953a and b). Stabell and Stabell (1982) found that discrimination was better developed in the temporal than the nasal field of view, but at angles greater than about 30 degrees from the fovea the visual system is effectively dichromatic, and at 45 degrees virtually all wavelengths appear identical in colour (Moreland and Cruz, 1959). It has also been demonstrated by Clarke (1960) that extra-foveal (10 degrees into the periphery) colour matches are not additive. A practical demonstration of the behaviour of this complex colour system can be found in the fact that a small, dim stimulus of particular dominant wavelength, changes its apparent colour, and may even disappear, as it is moved across the retina (Wooten and Wald, 1973). The quantitative effect is dependent on both size and intensity of the stimulus.

Small-field T-titanopia

When an observer with normal colour vision foveally fixates a small stimulus (20 minutes of arc, or smaller) his colour vision becomes dichromatic. Colour matches made for such small stimuli suggest that the blue mechanism is either not present or non-operative at the central fovea. Although Wald (1967) was unable to detect the blue-sensitive mechanism for fields of 7.5 min and smaller, it is possible that adaptation effects may account for the dichromatism for fields of up to 20 min (Ruddock and Burton, 1972).

Age

The ability to discriminate between colours improves into the early twenties, whereupon there is a gradual decline until, at the age of 60 - 65, this decline becomes more rapid.

Atmospheric effects

The effect of the atmosphere is to desaturate colours by the addition of scattered light. Under conditions where there is a significant amount of this scattered light in the atmosphere, stimuli can be considered to be approximately achromatic. The point at which colour is no longer visually important depends upon both atmospheric parameters (such as temperature and humidity) and upon the range of the stimulus and its perceived background.

Display considerations

The main advantage of using colour on displays would seem to be that dynamic range can be enhanced by the use of colour contrast in addition to luminance contrast. It is possible, however, that the

use of a wide range of colours could introduce effective clutter on a display, the result being a reduction of target conspicuity.

'Pseudocolour' has been used to code information in computer-generated or electro-optically-generated displays; for example, temperature can be coded into different hues when displaying a thermograph. This technique has been used to advantage in medical thermography, but attempts to use the same approach in coding spatial frequencies in radiographic images has been found to cause confusion. This may, of course, be due to the parameter being coded rather than the colours being used, and a great deal more research must be carried out in this area before definitive statements can be made.

Highly saturated colours can highlight physiological limitations within the eye. The accommodative mechanism appears to be most strongly activated by yellow light and less by other colours (Walls, 1943), the eye being very myopic (short-sighted) for blue light. These differences in accommodation probably result from longitudinal chromatic aberration in the eyeball and they can give isolated coloured objects a 'floating' effect when viewed against another colour of high saturation. Desaturation can be used to reduce the effect, but this also reduces the possibilities of using band-pass filters for contrast enhancement.

One very effective use of colour is as a specific indicator, ie red means 'danger', green means 'continue'. This can be implemented by an overlay technique (eg different coloured graticules to indicate different priorities) or warning lights appearing peripherally in the visual field of view. In this manner, the primary information and the overlayed information are processed independently within the brain.

3.4.3 Colour-defective vision

The most practical method of classifying colour-defective vision is to base the categories on subjective colour-matching characteristics. Individual colour-matching functions are subject to variations between different observers. Generally these differences do not result in improvement or degradation in the accuracy of matching different coloured stimuli. However, some observers produce matches which are outside the accepted limits of normal observer variability. Such individuals are said to have colour-defective vision, and represent about 8.6 percent of the Caucasian population. Most defects are related to the red-green mechanism and are genetically sex-linked, and this results in the fact that 8 percent of the population are male defectives and only 0.6 percent are female defectives (Nelson, 1938; Kalmus, 1965). There is a continuum of colour mechanisms from 'normal' to the most debased form of colour sense.

Defective colour vision can be broadly classified into three categories of observer.

- a Monochromats can match any two colours by adjusting their relative intensities. Cone monochromats have normal acuity

and normal photopic spectral sensitivity, in contrast to rod monochromats who possess poor visual acuity and exhibit only scotopic spectral sensitivity.

b Dichromats, as the term implies, can match any coloured stimulus using a mixture of only two primaries. They accept colour matches made by normal observers but confuse many colours which are distinguishable by normal observers. Three terms are used to describe the various forms of dichromacy.

- i Proctanopes are relatively insensitive to the red end of the spectrum and confuse all spectral stimuli of wavelength 530 nm and longer.
- ii Deuteranopes also confuse colours with wavelengths longer than 530 nm but see the visible spectrum as normal length.
- iii Tritanopes confuse colours at the blue-green end of the spectrum. They have approximately normal spectral sensitivity.

The simplest explanation is that each form of dichromacy represents the malfunction of one of the basic cone spectral responses; the red mechanism in the case of the protanope, the green mechanism in the case of the deuteranope and the blue mechanism in the case of the tritanope. The explanation given by Rushton (1963, 1965) is that the relevant cone pigments are missing at retinal level.

c Anomalous trichromats require a mixture of three primaries to match a given stimulus but their matches differ significantly from those of a normal observer. The simplest explanation, which is supported by psychophysical evidence, is that at least one of the three colour response mechanisms is abnormal, but still active. Protanomaly indicates a reduction in sensitivity of the red mechanism, deuteranomaly a reduction in the sensitivity of the green mechanism and tritanomaly a reduction in the sensitivity of the blue mechanism. In practice, protanomalous observers use too much of the red spectrum in their matching, whereas a deuteranomalous observer uses too much green. A tritanomalous observer would use too much blue, although such individuals are rare and there is even doubt about whether they really exist as a separate group (see Cole and Watkins, 1967).

An 'in depth' discussion of colour-defective vision would be necessarily involve much physiology and, as such, is not really appropriate in this report. Those wishing to study the deeper implications in respect of practical colour discrimination tasks are referred to Wyszecki and Stiles (1967). The table below shows the projected frequencies of the various forms of colour-defective vision from the data of Nelson (1938) and Kalmus (1965).

Type		Frequency
Monochromat	Rod	3×10^{-3}
	Cone	10^{-6} to 10^{-7}
Dichromat	Protanope	10^{-2}
	Deuteranope	10^{-2}
	Tritanope	10^{-4} to 2×10^{-5}
Anomalous Trichromat	Protanomalous	10^{-2}
	Deuteranomalous	5×10^{-2}
	Tritanomalous	$\sim 10^{-4}$ *

* No reliable data

Table 4 Frequencies of the different forms of colour defectiveness (From Ruddock, 1971)

3.5 Dynamic Effects

3.5.1 Single Pulse Stimuli

The temporal analogue of Ricco's law is called Bloch's law. This states that for short duration stimuli the eye acts as a complete integrator, ie for threshold stimuli

$$\int_0^T I(t)dt = \text{constant}$$

where I is the stimulus intensity at time t . The relationship holds for $0 < t \leq T$, where T is called the 'critical duration'.

The value of T may extend to 100 ms in the rod system and has a similar value in the cone system for low retinal illuminations, falling to between 35 and 60 ms at high (photopic) levels, the actual value of T varying between the different colour mechanisms (Krauskopf and Mollon, 1971; Uetsuki and Ikeda, 1971). The decrease in critical duration with increasing adaptation level has been quantified by Matin (1968) who showed that $1/T$ varies logarithmically with retinal adaptation level.

Higher order tasks such as acuity and recognition are associated with higher values of T (Kahneman and Norman, 1964), movement of the stimulus eliciting values as high as 400 ms (van den Brink, 1957).

For stimuli with durations substantially longer than T the threshold law becomes

I = constant

Figure 41 shows some typical results obtained by Roufs (1972).

Single-pulse stimuli, together with two or more flashes, have been used to study the basic temporal summation process within the visual system (Ganz, 1975). However, for practical display situations the visual response to flicker is a more important parameter.

3.5.2 Flickering Stimuli

If a stimulus is presented repetitively then flicker is perceived at low temporal frequencies. As the flicker rate is increased, a frequency is reached, beyond which the stimulus is seen as continuous in time. The frequency at which this occurs is called the critical fusion frequency (CFF). The literature on this topic is vast but some general results are relevant to display design.

The relationship between CFF (F_c) and the luminance of the stimulus is given by the Ferry-Porter law:

$$F_c = a \cdot \log L + b$$

where a and b are constants which depend on such parameters as size, retinal position and wavelength composition of the stimulus. Figure 42 shows the dependency of CFF on these parameters. For a stimulus which is alternately on and off, such curves represent the temporal analogue of visual acuity. The temporal analogue of the contrast sensitivity function is shown in Figure 43. The modulation contrast threshold is shown as a function of critical fusion frequency. It is clear that the temporal profile is of minimal importance.

Kelly (1961) measured absolute amplitude sensitivity against modulation frequency and his results are shown in Figure 44. Supra-threshold flicker is often useful as a means of alerting an observer, and Barmack and Sinaiko (1966) have defined certain frequencies to cause specific effects:

Below 3 Hz	Good at alerting (especially in directing attention away from a display being fixated).
4 - 7 Hz	Slight perceptual discomfort (tolerable).
8 - 15 Hz	Can cause confusion, even loss of consciousness in some observers, and may even induce fits in people prone to epilepsy.
15 - 30 Hz	Distractive only.

Spatio-temporal interactions have been studied by various researchers and an example is shown in Figure 45. Kelly (1966) has produced a three-dimensional spatio-temporal threshold surface (Figure 46) which demonstrates the complex dependence of threshold modulation on both spatial and temporal frequency.

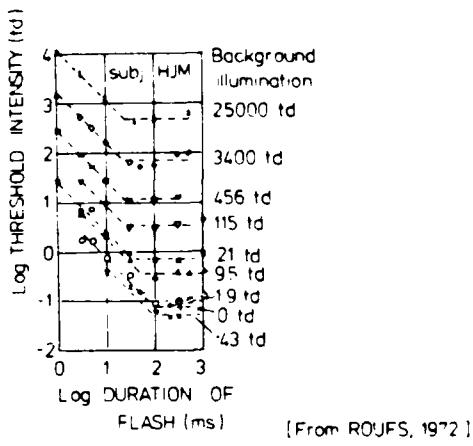


FIG.41 THRESHOLD INTENSITY VERSUS FLASH DURATION FOR A 1° FOVEAL STIMULUS

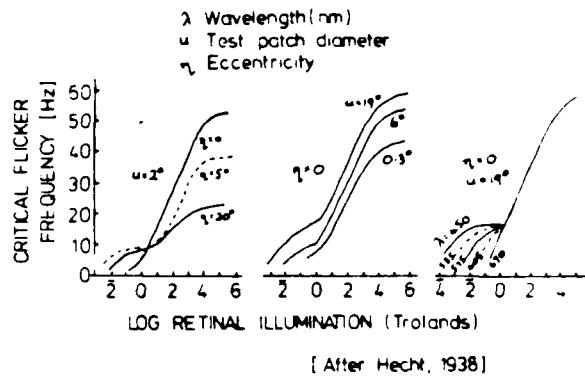


FIG.42 DEPENDENCE OF CRITICAL FLICKER FREQUENCY ON SIZE, WAVELENGTH, RETINAL POSITION AND ILLUMINATION

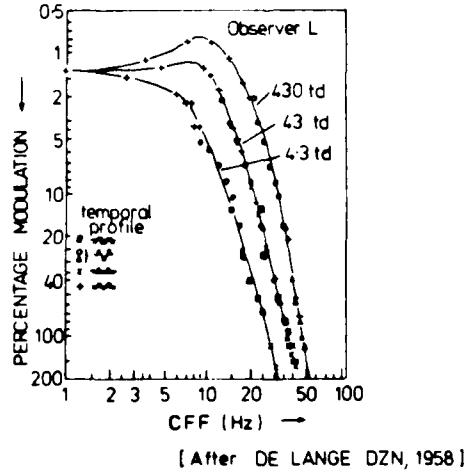
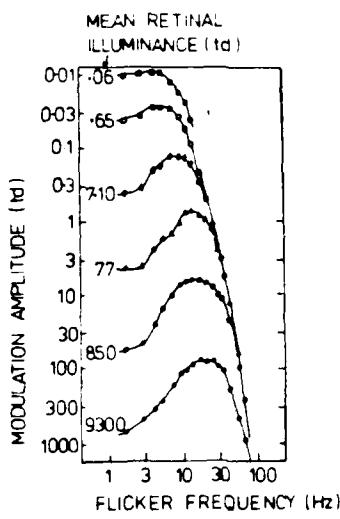
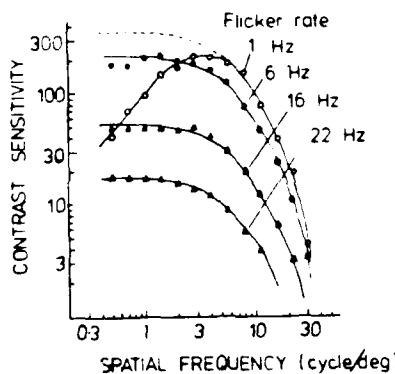


FIG.43 MODULATION CONTRAST THRESHOLD AS A FUNCTION OF FLICKER FUSION FREQUENCY FOR THREE MEAN LUMINANCE LEVELS



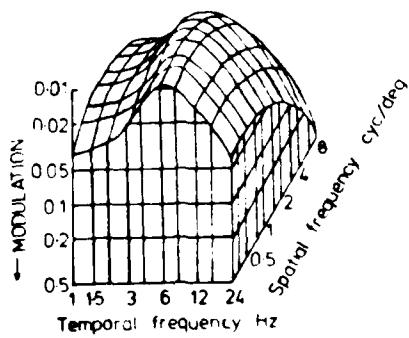
[After KELLY, 1961]

FIG.44 THRESHOLD MODULATION VERSUS FLICKER FREQUENCY



[After ROBSON, 1966]

FIG.45 THE EFFECT OF FLICKER ON THE CONTRAST SENSITIVITY FUNCTION



[After KELLY, 1966]

FIG.46 THREE DIMENSIONAL SPATIOTEMPORAL THRESHOLD SURFACE

For practical displays, luminance and phosphor characteristics can be manipulated together with raster interlacing to produce an optimally displayed image. The interested display designer is referred to Turnage (1966), Dill and Gould (1970) and Humes and Bauerschmidt (1968) for discussions of the relevant trade-offs.

3.5.3 Moving Stimuli

If the eye tracks a moving, suprathreshold target so that it remains on the fovea, then the measured acuity depends on the eye's ability to track the stimulus accurately. Figure 16 shows the general trend which is a linear reduction of acuity with velocity up to 80 deg s^{-1} . Beyond this velocity the degradation in acuity accelerates. The results shown in Figure 16 agree with those of other studies (Miller and Ludvigh, 1962; Snyder and Greening, 1965; Burg, 1966).

Burg and Hulbert (1961) have shown that dynamic visual acuity can be improved through both practice and increased illumination. It appears that superior dynamic acuity is measured for stimuli moving in a vertical plane in comparison to that obtained with horizontal motion (Miller and Ludvigh, 1953).

For non-fixated stimuli, Low (1947) has shown that peripheral dynamic acuity is significantly lower than static acuity at corresponding retinal locations.

Another method of quantifying the visual effect of target motion is to measure the threshold for movement detection. This can be done either by measuring the threshold velocity for a fixed target contrast or by measuring threshold contrast for a fixed target velocity. The detection of movement, especially that occurring in the peripheral retina, is relevant to the design of instruments and displays where linear or rotary movements of indicators are involved. McColgin (1960) reported a study which has direct relevance to such displays.

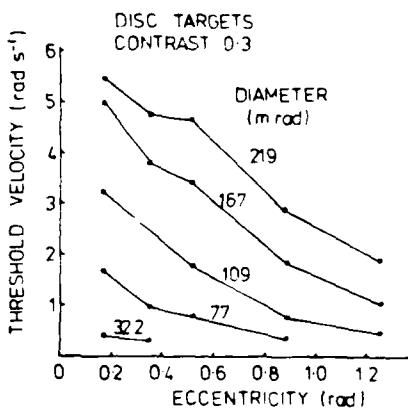
More general studies involve the measurement of dynamic sensitivity at various retinal positions when the stimulus is in the presence of different amounts of background structure. Figure 47 shows threshold velocity plotted against eccentric angle from the fovea, for disc targets of varying diameters.

Another method of quantifying sensitivity to movement is to measure luminance increment thresholds as a function of target speed. Barbur (1980) has compared foveal and peripheral sensitivity with and without background structure (see Figures 48-50).

Some general conclusions can be reached. The peripheral retina is less sensitive than the fovea for small moving targets. The periphery becomes more contrast-sensitive than the fovea to the movement of large objects moving at high speed. More information is required on the detection of very slow movement, especially that involving small stimuli against cluttered backgrounds.

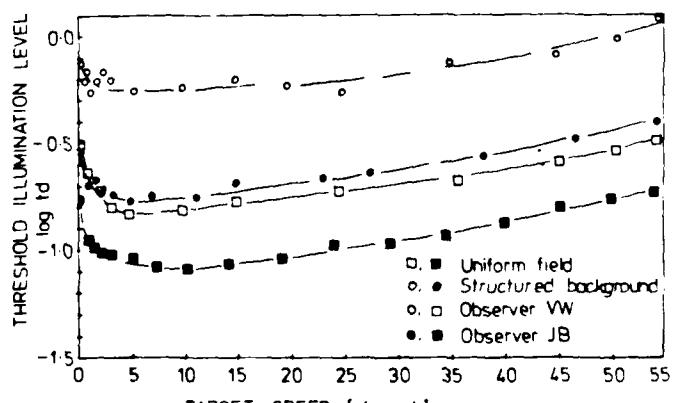
3.5.4 Visual Search

When searching for a stimulus at an unknown location within a given field of view, the eye scans the scene in a series of jumps, each of



From data of LAVIN and SPICER (1972)

FIG.47 VELOCITY THRESHOLDS FOR VARYING MEAN VIEWING ECCENTRICITY



From BARBUR (1979)

FIG.48 FOVEAL INCREMENT THRESHOLD ILLUMINATION CURVES AS A FUNCTION OF SPEED FOR UNIFORM AND STRUCTURED BACKGROUNDS

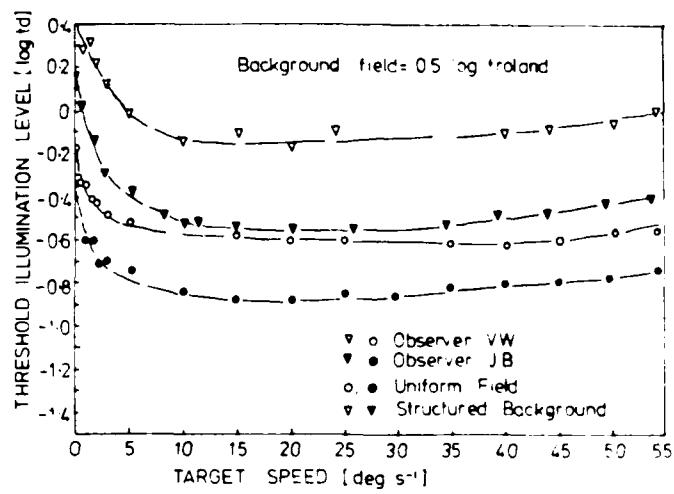
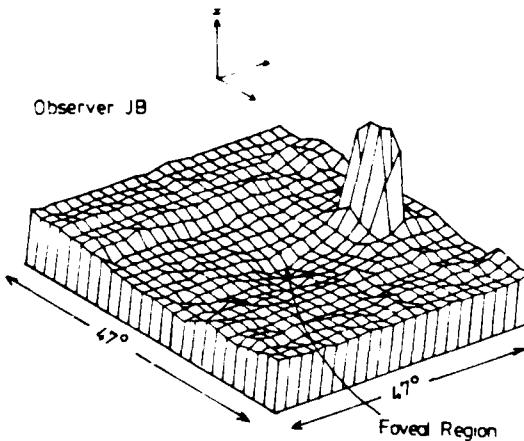


FIG.49 PERIPHERAL INCREMENT THRESHOLD ILLUMINATION CURVES AS A FUNCTION OF SPEED FOR UNIFORM AND STRUCTURED BACKGROUND FIELDS



From BARBUR (1979)

FIG.50 3-DIMENSIONAL REPRESENTATION OF THE SENSITIVITY OF THE CENTRAL RETINA TO MOVEMENT. Z CO-ORDINATE IS PROPORTIONAL TO THE LOGARITHM OF THRESHOLD ILLUMINATION LEVEL REQUIRED FOR THE DETECTION OF THE 1.2° TEST TARGET

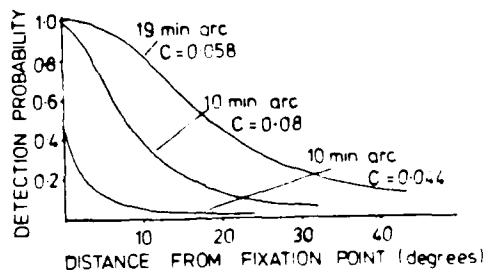
which terminates with a period of fixation. It is conventional to call this period of fixation (or dwell period) a 'glimpse'. During a 'glimpse' the probability of detecting a target within the field of view of the eye varies with its position within that field of view. The variation of probability of acquisition with angular distance from the fixation point is called a 'visual lobe' (Davies, 1968). An example of visual lobes for isolated, circular targets of varying size and contrast is shown in Figure 51. In practice, these lobes are target- and background-dependent. The idea of a 'glimpse' and a 'visual lobe', together with knowledge of the eye movements during the search task, provide the basis for much visual search modelling (Morris and Horne, 1960).

Visual search performance depends on the form of both target and background, on the instructions given to the observer and on his past experience. This makes the search task difficult to model but two attempts involving military search are those by the NV & EO Laboratories (Lawson and Shields, 1980) and by British Aerospace (Brown, 1980). An extensive bibliography on all aspects of visual search is given by Carr et al (1983). There follows a description of some of the more general results of visual search studies.

As mentioned above, the eye searches in a series of 'glimpses' which occur at the rate of approximately 3 per second for free search (Ford et al, 1959), although this rate depends upon the conceptual difficulty of the task (Gould and Dill, 1969). These glimpses are separated by fast eye movements, or saccades, at a mean angular rate of some 300 deg sec^{-1} .

The dwell time includes both the integration time of the visual system plus some time element for the decision-making process about how the eye must move for the next 'glimpse'. The distribution and sizes of the eye-movements depend upon the nature and size of the displayed scene and upon observer experience. Enoch (1959) found that observers viewing aerial maps fixated mainly at the centre of the display. Interfixation distances increased and fixation times decreased as the angular size of the display was increased. Search efficiency was significantly reduced for a displayed image subtending less than 9 degrees, because the observer spent considerable time looking outside the display area. Enoch's study involved constant size information, ie increasing the size of the display simply added extra information at the same magnification. A study by Goillau (1982) measured the effect of increasing display size of a fixed scene, ie the magnification was changed. This study showed that probability of detecting a given target increases to an optimum display size of approximately 45 degrees (Figure 52). A study by Farrell and Booth (1975) adds support to this result in concluding that little can be gained from making display sizes greater than 60 degrees.

It has been found, not surprisingly, that eye fixations for military surveillance tasks are clustered around features within a scene which are most likely to contain a target. The distribution of fixations is also highly dependent on the observer's training, and this becomes more evident when observers use specialised electro-optical systems. Krebs (1975) compared the performance of novice with trained



[After BROWN, 1979]

FIG.51 EXAMPLES OF VISUAL LOBES
C IS TARGET CONTRAST

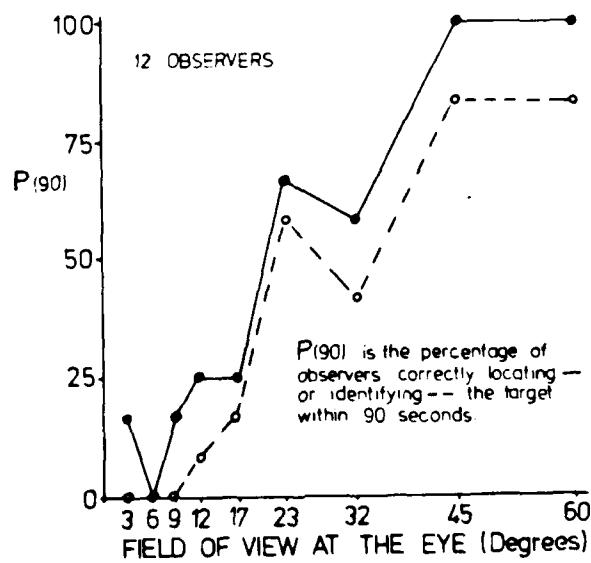


FIG.52 EFFECT OF FIELD SIZE ON SEARCH
[From GOILLAU, 1982]

subjects and found that the novices tended to concentrate their fixations at the centre of a FLIR display, whereas trained subjects searched a greater display area more quickly, either by executing larger saccades or by reducing fixation times.

The modelling of visual search requires quantitative information on search strategies which are adopted under particular conditions. It also requires information on feature extraction by the visual system, so that eye movement patterns can be predicted quantitatively for given targets and backgrounds. Improvements in eye-tracking techniques are making quantitative results easier to obtain, but there is still a long way to go before a definitive visual search model can be produced.

3.6 Visual Noise

Visual noise is defined as any visual signal which acts so as to mask a stimulus of interest. On the basis of this definition visual noise can be divided into three broad categories:

- a Inherent noise within the visual system
- b External system noise
- c Background clutter

Each of these is discussed below.

3.6.1 Visual System Noise

The components of noise within the visual system are:

- i Inherent optical aberrations
- ii Receptor sampling effects
- iii Temporal blurring caused by eye movements
- iv Veiling glare within the eyeball
- v Receptor and transmission noise.

i and ii are reflected in the measurements of performance such as visual acuity and contrast sensitivity. iii is a necessary part of the visual process, either to provide a dynamic signal to the receptors or to locate the fovea(s) in the direction of attention. Large saccades involve periods of rapid eye movement through tens of degrees. The visual system masks the blurred image during such a movement (Campbell and Wurtz, 1978) and this results in our continuous, clear perception of the world. iv becomes significant only for high photopic levels of illumination, or for bright, off-axis sources. v affects the measurement of thresholds and perception of very high contrast stimuli which cause after-images. iv and v require further explanation.

iv Glare

Peripheral glare sources have an additional effect on central (foveal) vision and can be calculated (Holladay, 1926). Optimum contrast sensitivity is achieved when the surrounding illumination is equal to that at the displayed image. Ireland et al (1967) have produced an empirically-based formula which predicts contrast threshold, C , for a given ratio of surround to display luminance, $L_s/L_d > 1$

$$C = C_0 (0.9815 + 0.0185 L_s/L_d)$$

C_0 is the threshold contrast for $L_s/L_d = 1$.

When the mean ambient illumination increases to the level where the pupil can constrict no further, then internal glare within the eyeball tends to reduce the contrast of the retinal image. The effect of such glare is to cause a fall-off in visual acuity and contrast sensitivity at very high illuminations. The level at which this occurs is observer-dependent, but for practical purposes applies only to environments such as aircraft cockpits where the illumination rises above 10^4 lux.

v Receptor and Neural Noise

The final output from retinal level comes from the ganglion cells, at which point intensity is coded in terms of frequency modulation, ie firing rate of the cell. The greatest rate of change occurs at the onset and offset of a stimulus. Because of the horizontal connections within the retina, this firing rate becomes an average of increasing numbers of components as retinal eccentricity is increased. A brief description is given in the next section of how statistical communication theory can be used to explain the uncertainty of visual thresholds.

A specific form of noise which can exist within the receptor/neural network is an after-image. This is a residual perceptual effect which remains when the original stimulus is removed. It is possible to produce both positive and negative after-images, ie the after-image produced by a stimulus of positive contrast may appear to have either positive or negative contrast. The rules governing the polarity of such an after-image are complicated and the polarity may even alternate with time. Generally speaking, short intense flashes produce predominantly positive after-images, and longer-duration stimuli produce negative after-images. The fact that after-images are stabilised on the retina means that they are dimly perceived (Riggs et al, 1953) but the effect is to raise the increment threshold in the area of the after-image to that of the equivalent background luminance (Barlow, 1964). Coloured stimuli can cause coloured after-images which may appear with either polarity. A negative after-image has an approximately complementary hue to that of the stimulus, ie a red stimulus results in a blue-green after-image, a yellow stimulus induces a blue after-image, etc. Very strong stimuli can cause an after-image which reduces the sensitivity of the retina in the region of the image virtually to zero, and renders it effectively blind. As the dark adaptation curve (Figure 10) indicates, the reduction in sensitivity can last for many minutes.

3.6.2 External System Noise

One method which has been used to describe the basic visual detection mechanism is based on statistical communication theory. Although a complete description of the technique is not practicable in a report such as this, a brief summary is given to indicate the relevance of the approach to electro-optical system displays.

At very low levels of incident radiation it becomes clear that the quantum nature of light plays a direct part in the uncertainty of a visual threshold. Although a retinal rod is capable of being stimulated by the absorption of a single quantum, 5 to 8-fold coincidence of quanta is required to evoke a visual response (Hecht et al, 1942). Allowing for absorption and reflection of quanta as they pass through the eyeball to the retina, about 100 quanta incident on the front surface of the cornea would be sufficient for 10 to reach the photosensitive receptors. The Poissonian distribution of quanta emitted (as random discrete events) from a light source, gives good agreement with experimental frequency-of-seeing curves for absolute visual thresholds (Hecht et al, 1942); Pirenne and Marriott, 1955).

Rose (1942) and de Vries (1943) postulated that statistical fluctuations in the absorption of quanta would limit visual performance at higher luminance levels. In fact, for other thresholds the frequency-of-seeing curves exhibit the same basic sigmoid shape and can be represented theoretically by a normal ogive (Blackwell, 1952). It should be emphasised that this is only an approximate mathematical representation of what is fundamentally an experimental result (Figure 53). So many factors contribute to the shape of the resultant curve that no single theory can predict the results of all experiments. However, the concept of 'noise-required input contrast' of the visual system has been used to model visual performance using electro-optical displays. Schnitzler (1973) gives a good historical review of the topic, and Rosell and Willson (1973) show how visual performance has been measured in terms of the display signal-to-noise ratio concept. Figure 54 shows an example of how visual performance data for the detection of simple bar targets can be represented in terms of display signal-to-noise ratio. Johnson (1958) found that it was possible empirically to relate the probabilities of detection, recognition and identification of complex targets to the probability of detection of simple multiple-bar test patterns. These Johnson criteria have been used, with some modifications, as an important part of many electro-optical system models (eg the NV&EO Laboratories Systems Model, described by Lawson and Shields, 1980) where the final image is noise-limited.

Visual thresholds when viewing through image intensifier systems can be predicted by a theory, developed by Beurle et al (1969) and Hodgson et al (1971), which accounts for scintillation noise. It has been shown that for cascade tube intensifiers there is an optimum gain, G , above which no improvement to detection threshold is obtained. For low scintillation densities the threshold may even rise for gains greater than G . Hirst et al (1979) have suggested that accurate scintillation counting occurs for low scintillation densities. Channel plate devices, which exhibit a negative exponential pulse height distribution, give higher contrast thresholds when scintillations are

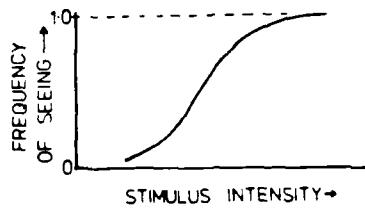


FIG.53 GENERAL FORM OF THE VISUAL THRESHOLD RESPONSE

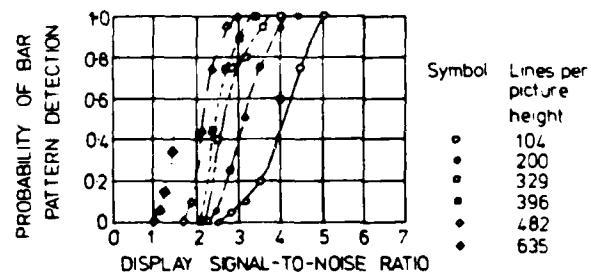


FIG. 54 PROBABILITY OF DETECTING BAR PATTERNS OF DIFFERENT FREQUENCIES ON A NOISY DISPLAY

[From ROSELL and WILLSON, 1973]

visible (Beurle and Moy, 1981). It appears that visual summation times provide an explanation. With the exponential pulse height distribution the eye attempts to produce a lower signal-to-noise ratio at the expense of temporal response.

Braccini et al (1980) have shown that correlated binocular noise significantly reduces binocular summation. That is, if the noise entering each eye is identical point-to-point across the image, then the binocular contrast threshold is higher than that obtained when the two noise patterns are only statistically identical. There are clear implications for night goggles which use image intensifier tubes.

It should be pointed out that fixed pattern noise can cause spatial-frequency masking (Stromeyer and Julesz, 1972) and should be avoided as far as possible. For example, visible raster lines having high contrast against the black level of a display can mask spatial frequencies within a octave of their own frequency. A similar effect is possible with the background structure introduced by channel plates. In many cases the best remedy is to increase the viewing distance until the structure is no longer visible.

3.6.3 Background Clutter

The presence of background structure may have a highly significant effect on visual acquisition performance. The degree to which the structure affects the acquisition process depends on the exact composition of both target and background. The general trend is for structure within the scene to degrade visual performance with respect to that exhibited for empty field viewing: hence the use of the word 'clutter'.

The interactive effect of a background on the detection of a stimulus can be three-fold.

- i A complex set of local contrast differences can be set up along the profile of the stimulus. The effect of this on the detectability of the stimulus depends on both the size and the overall contrast of the stimulus.
- ii Strong, unwanted stimuli in the proximity of the stimulus of interest can distract the eye, and hence modify the distribution of eye-movements and fixation times during a search task.
- iii Structure can desensitise the visual system to spatial frequencies contained in the background in the same way as fixed-pattern display noise. In this respect, clutter which contains elements of similar size to that of the target has the most degrading effect on performance. It should be noted that sub-threshold structures may influence visual sensitivity to stimuli contained within a scene (see for example Fiorentini and Maffei, 1970; Kulikowski and King-Smith, 1973; Bagrash et al, 1974).

The overall effects of background clutter on visual search is that both visual lobes and search patterns are modified. Engel (1977)

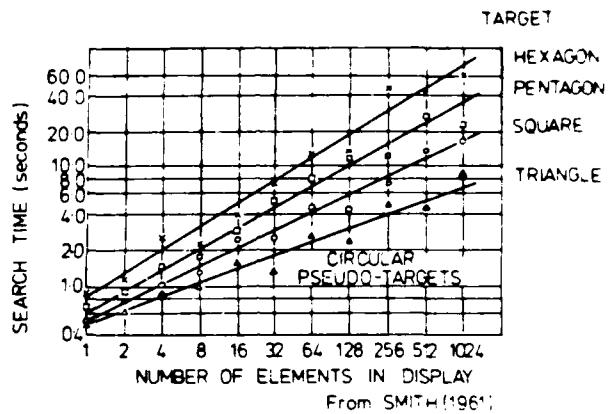


FIG. 55 SEARCH TIME AS A FUNCTION OF THE NUMBER OF PSEUDO-TARGETS

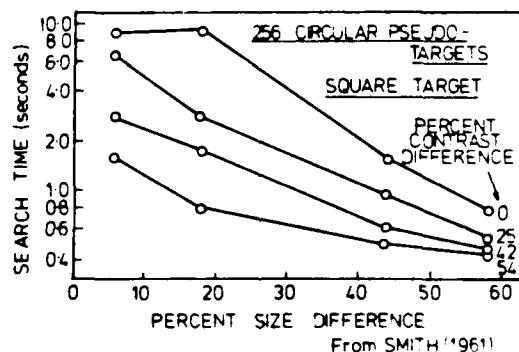


FIG. 56 SEARCH TIME AS A FUNCTION OF SIZE AND CONTRAST DIFFERENCE BETWEEN TARGETS AND PSEUDO-TARGETS

has found that 'non-targets' are fixated spontaneously in proportion to their conspicuity area, which he defines as the visual field in which the target can be discovered after a single eye fixation.

Modelling the effects of background clutter depends upon our ability to describe it, and for most practical situations this is very difficult. Most practical models of visual target acquisition involve a 'field factor' which quantifies the degree of degradation of performance with a cluttered scene over that with a structureless background.

A study by Smith (1961) on complex, abstract, visual displays indicated trends which are likely to apply to real scenes. Figure 55 shows the effect on search time of increasing the number of pseudo-targets on the display. From the results it is clear that search times increase as the pseudo-target shape becomes closer to that of the stimulus. Similarly, pseudo-targets of similar size to that of the stimulus cause most degradation in the search rate (Figure 56).

The degree of influence of such factors as target size and shape will always depend upon the knowledge, or the instructions given to an observer. If he is told to look for a horse against trees, with the knowledge that there are no other animals in the scene, this is a far easier task than searching for the same horse within a scene known to include trees, bushes and buildings, and with the knowledge that other animals may also appear within the scene. The observer may be able to ignore extra-foveal trees without looking at them directly, but would probably have to fixate on a cow before he could resolve enough detail to reject it as a target.

This section can do little to assist the vision modeller, except perhaps to indicate the problems involved in specifying tasks and performance measurements for studies with cluttered scenes. It must be emphasised that, although it is possible to bias out the background with some AC systems such as thermal imagers, background is usually required so that the observer can orientate himself. A switchable system may allow the designer to overcome this apparent dichotomy of requirement.

4 DISPLAY CONSIDERATIONS

General parametric requirements

Although the specific parameters of a display will depend upon the task at hand, it is possible to list some general observations.

- i The eye performs best at luminances of between 50 and 5000 Cd m⁻². For high resolution tasks it is essential to provide a display luminance which falls within these limits.
- ii Ignoring other limitations such as bandwidth, raster frequency etc, a large display angle ($> 30^\circ$) is necessary to optimise performance by minimising edge effects.
- iii The optimum viewing distance for a display is between 0.5 and 1.0 metre, in order to obtain accurate visual accommodation. This distance is more critical for low-contrast information, and is observer-dependent.

- iv Maximum photopic sensitivity is achieved in the green region of the spectrum, although acuity is unaffected provided that luminance is held constant.
- v The use of colours on displays should be considered carefully. It is possible to use colour to increase the dynamic range of a display, but certain situations should be avoided. Small blue stimuli should be avoided because of the small-field tritanopia of the central retina. Highly saturated colour contrast can cause problems with accommodation, resulting in a 'floating effect' in some situations. Desaturation of the colour alleviates the accommodation problem but limits the use of band-pass contrast-enhancement filters. The use of many different hues can cause confusion of information, especially where unusual coding techniques are being used.
- vi For displays with TV-like bandwidths and luminances, the RMS luminance fluctuation due to noise should be approximately 1% of the peak luminance in order to reduce the noise below the level of objectionability (Cohen, 1978). This implies a required signal-to-noise ratio of $20\log_{10} 100 = 40$ dB.
- vii The refresh rate of a display should be high enough to avoid the perception of flicker. The actual rate required depends upon luminance and display size. For normal room levels of illumination, a refresh rate of ~40 Hz (non-interlaced) would suffice for most common phosphors. Higher luminance displays, such as those used in aircraft cockpits, require up to 80 Hz to eliminate flicker (Lavcock and Chorley, 1980). The CFF decreases away from the fovea, thus limiting the angular size of practical displays.
- viii Warning lights and alerting signals are best introduced away from the line-of-sight and flickered at 3 Hz or lower frequencies. 8 to 15 Hz flicker should be avoided for all but malevolent purposes.
- ix It is possible to obtain 'beating' between adjacent displays where inter-display synchronisation is absent. This can cause discomfort from otherwise acceptable devices.
- x Visible structure, which is not part of the displayed information, should be avoided if possible.
- xi Binocular displays have certain advantages over monocular systems. Comfort is greater, the blind spot of each eye is compensated by the other eye, and contrast sensitivity is enhanced significantly. However, care must be taken in designing a binocular display so that binocular convergence is correct for the final image distance. Differences in magnification in the two channels can cause rivalry and loss of performance, as do differences in the image content if the images are incompatible. It should be remembered that binocularly correlated dynamic noise causes a reduction in contrast sensitivity compared to the case of uncorrelated noise.

For practical displays the reduction of image contrast caused by ambient illumination can cause an effective reduction in dynamic range of the device, and various techniques have been used to enhance the image contrast (see for example Miyazaki, 1980; Izumitani et al, 1980; Trond, 1980; Yarger and Waruszewski, 1980).

5 CONCLUSION

A summary of the visual performance data of the human visual system has been given. Although a great deal of information has been obtained, it is clear from the data that a large number of very complex topics require much more research. It is usually when the data obtained under the simplified conditions of a laboratory must be applied to visual performance in everyday tasks that problems arise. It is hoped that the data presented here will assist the designer of display systems to avoid any of the obvious pitfalls highlighted in the published literature, and may even suggest new techniques for improving display design.

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Abstract This report has been written after several seminars within RSRE had highlighted a number of disturbing facts. Firstly, there is very little dialogue between the designers of displays and the vision researchers. Secondly, although a great deal of information exists on the performance of the eye, it is often obscure and the practical implications are not clear. Thirdly, for a display engineer who is not necessarily interested in the fine detail of the visual mechanisms, sources of practical data covering the whole subject of human vision are scarce.			
continued			

A brief description of the physical properties of the eye is given together with an account of the various methods of measuring observer performance. The diagrams are provided as a means of indicating general trends with a minimum of descriptive narrative. A broad bibliography is included so that those interested in specific topics can follow them up.

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